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Systematic tool to plan and evaluate demand side strategies during sustained energy crises in hydrothermal power systems

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ABSTRACT

HARE, a systematic tool to evaluate demand side measures to face sustained energy supply risk in hydrothermal power systems is presented in this paper. The main focus of the paper is to help centralized planners to systematically discuss, select, and plan the measures that better respond to the variety of critical situations that can arise due to expected energy shortage, integrate them into the usual medium-term scheduling tool and consequently keep the associated overall costs as low as possible. A medium-term definition of the system state is proposed as a decision-making aid, as well as a set of general energy saving measures that can be applied with their corresponding attributes (time delays, costs of implementation, and energy saving impact). The tool is demonstrated and applied to a simplified version of Chilean's medium-term hydrothermal scheduling model and to a specific risk scenario experienced during 2011. The results show that it is possible to define various sets of demand side measures that avoid the impacts on the system and subsequently to select among them those with least expected implementation costs. This tool seems mainly useful for hydro-electric systems, which are more vulnerable to sustained energy supply risk. Every power system will have to go through a detailed review and planning process to implement this type of tool.

Introduction

International context

In the current privatization and deregulation environment, one of the main problems that electricity markets have to address is the adequate expansion of generation capacity and transmission networks so that demand can be met. Adequacy is a mid/long term problem that also involves the appropriate provision of resources to meet the demand, which is particularly critical in hydrothermal systems, due to the challenges related to the management of the hydro resources stored in the reservoirs. This problem resides within a broader set of challenges in every country related to energy security provision, which involves the development of policies to avoid and/or face potential crises. In all cases it will be clear that a reasonable adequacy policy takes into account some level of risk of deficit in which not all demand can be met.

When a power system threatens to become incapable of serving demand in a sustained way after applying all the actions available under its normal market organization, it becomes necessary to implement extraordinary preventative rationing measures (e.g. voltage reduction in distribution networks, quota systems, energy reduction campaigns) to avoid using rolling blackouts to keep the system balanced.[1] Usually the task of choosing those measures is done under extreme pressure because of the proximity of the expected shortage, which can lead to wrong decisions, hence yielding a suboptimal scenario with high social costs [10]. This short-term decision-making can also lead to unnecessary market distortions and 'gaming' in anticipation of such (political) intervention. Preferably, the design of such sets of measures should be conducted in an organized way, ahead of time, to efficiently minimize the negative impact of the imbalance and prepare the market. In particular, measures on the demand side are likely to help the situation in a very effective way because diminishing consumption directly reestablishes the balance between the demand and a limited energy/power supply. Therefore, measures associated to the demand side are the main focus of this work.

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[1] It is important to differentiate between preventive and mandatory rationing periods. The latter refers to periods in which extraordinary measures are taken along with rolling blackouts to overcome the effects of an energy constrained system, whereas a preventive rationing period describes a situation where extraordinary measures are taken in advance to explicitly avoid the need of rolling blackouts.

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Nomenclature

Functions

C_{TG_i}	cost function of thermal generator *i*
C_{UE_j}	unserved energy cost function for load *j*

Parameters

β_q	cost of unserved irrigation water
p_{L_j}	expected power consumption of load *j*
x_{ij}	line reactance between bus *i*th and bus *j*
$\overline{f}_{ij}$	max transfer between bus *i* and bus *j*
$\underline{f}_{ij}$	max reversed transfer between bus *i* and bus *j*
N_B	number of buses
N_{TG}	number of thermal generators
N_L	number of loads
N_I	number of extractions for irrigation
ϑ_j	future cost function linear approximation *j*
$\alpha_{L_j}^{t,b}$	lower bound reduction factor of load *j*
$\beta_{L_j}^{t,b}$	upper bound reduction factor of load *j*
σ	global energy reduction factor
IM_{ij}	interaction factor of measure *j* on measure *i*
$\phi^{t,b}$	total costs of operation from stage *t* block *b*
$\underline{H}$	incidence matrix of hydro-related constraints
$\vec{b}$	right hand side vector of hydraulic constraints

Sets and indices

t	time index (stage)
b	demand block index
Ω_{G_i}	set of generators connected to bus *i*
Ω_{L_i}	set of loads connected to bus *i*
Ω_{BB_i}	set of buses connected to bus *i*
Ω_{BB}	set of buses in the system
Ω_{S_p}	set of measures associated to strategy *p*
φ	set of expected future cost function cuts

Variables

p_{G_j}	power output of unit *j*
p_{U_j}	unserved power of load *j*
$p_{T_{ij}}$	power transferred from bus *i* to bus *j*
θ_i	phase angle of bus *i*
q_{U_k}	unserved flow of irrigation *k*
δ_{L_j}	power consumption of load *j*
ϑ	future cost
$\overrightarrow{\theta}$	vector of phase angle variables
$\overrightarrow{p}$	vector of power output variables of all units
$\overrightarrow{p_H}$	vector of power output variables (hydro units)
$\overrightarrow{\delta}$	vector of demand variables
$\overrightarrow{q}$	vector of flow variables
$\overrightarrow{v}$	vector of volume variables

The analysis of the best measures to apply in a certain situation relies on two main factors. On the one hand, it is necessary to modify the usual models to study the systems' adequacy in order to be able to determine the degree of deficit risk being faced by a system, which in case of hydrothermal systems with large reservoirs is represented by mid-term (up to 24 months in the Chilean case) hydrothermal coordination. On the other hand, an overview of available measures, their potential (demand reduction) impact and costs (economic and political) is necessary.

Sustained deficits have been faced by several countries around the world despite of their market structure and generation mix as reported by [10,5,1], many of these are hydro-dominated electricity systems. Fig. 1 shows some of the major sustained energy crises around the world and the main sources of the problem: unexpected demand growth (*U*), extreme temperatures (*E*), droughts (*D*), lack of investment in new generation (*I*), financial problems/liquidity of generators (*L*), extended failure/maintenance of critical generators in the system (*M*), failed market reforms (*R*), and transmission constraints (*T*) among other causes.

The challenge of including the effects of scarcity periods in the long-term hydrothermal coordination has been studied only in a few cases, in particular for the energy crisis in Brazil in 2001. Marcato et al. [8] study the effects on the prices and the operation of the system by including the characteristics of a rationing period (recreating the situation experienced in Brazil) in the long-term optimization of the system. Carreno et al. [2] describe the influence of the rationing period on the consumer behavior during the Brazilian energy crisis in 2001. Galetovic and Muñoz [4] determine the impact on the index of deficit probability when the long-run price elasticity of the demand is taken into consideration. Kelman et al. [7] define an index of probability for the enforcement of a rationing period by the Brazilian government, considering the context in which the regulator has high incentives to impose such a regime.

The New Zealand electricity market – though not centrally planned – has also invested significant effort to come to a coordinated Emergency Response after droughts in 2001, 2003 and 2008, including staged response in what are called Watch, Alert and Emergency stages depending on the probability of future supply shortages under expected demand, supply and rainfall scenarios [15].

Chilean experience in rationing management

The Chilean Power System was liberalized in 1982, following a mandatory pool structure at generation level with bilateral financial contracts between generators and large customers. The initial structure remains, along with the liberal orientation of the reform, but is has been modified throughout the years to improve its weaknesses, yielding the organization described in [4]. The system has a large amount of hydropower, with important storage capacity (approx. 9 TW h, 22% of the energy generated in 2010), which is highly concentrated in the Lake Laja (approx. 7 TW h), the main reservoir of the system and a good reference for resource availability. The penetration of non-conventional renewable energy[2] remains low (around 2.8% total generated energy in 2011). As shown in Fig. 2, the system faced a major drought in 1998–1999, which had mayor impact on the Central Interconnected System (SIC), leading to the use of rolling blackouts (mandatory rationing) and to important changes in the structure of the law, regulating the force-majeure conditions and the associated compensations to the regulated end users. The law has given powers to the regulator to establish a special regime of operation if scarcity is foreseen. That power has been used three times since the system was liberalized (yellow circles in Fig. 2 shows the start of the rationing period, which usually lasts 6–12 months). Apart from the situation in 1999, when the system was actually close to a complete energy deficit (visible in Fig. 2 in terms of lake level and installed thermal capacity being much lower than

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[2] Non-conventional Renewable Energies are all the generation systems connected to the respective power system, and which energy source is nonconventional, as geothermal power, wind power, solar power, tidal power, hydro power under 20 MW of installed capacity, cogeneration and other similar determined fundamentally by the Chilean Energy Commission.

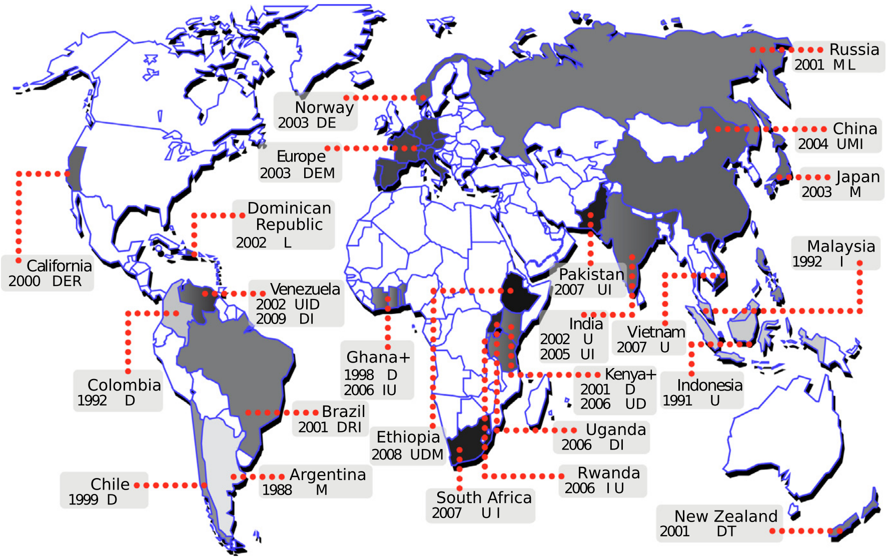

Fig. 1. Examples of major sustained energy crises that have arisen around the world by year and cause(s).

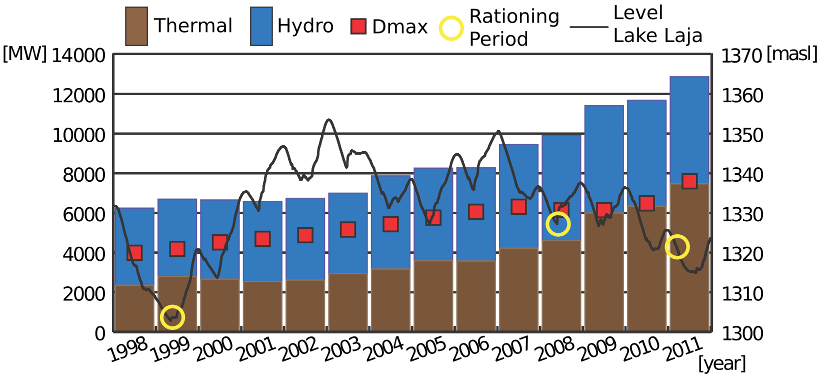

Fig. 2. Yearly installed capacity by type, peak demand, Laja lake storage level (measured in meters above sea level, masl), and rationing periods from 1998 to 2011 in the Central Interconnected System (SIC). (Data source: CDEC-SIC).

maximum demand), the other two rationing periods were preventive and - in the end - no rolling blackouts were necessary. In years 2008 and 2011 the hydro resources were not as scarce as in 1999; however, transmission constraints and the lack of water in smaller reservoirs led to the need of special measures to avoid sustained local scarcity.

It is interesting to underline that the enforcement of a rationing period in Chile includes several measures that cover different aspects concerning the operation of the system, namely, water usage constraints, transmission and generation slack, demand management, among others. All the examples of rationing plans implemented in Chile show a very similar structure in terms of the measures applied even though the scenario was very different in each case.

Aims and structure of the paper

The abovementioned dissociation between implemented demand-side measures and the scenario being faced is the central motivation of this work, because it suggests the response was not optimally adapted to the situation being faced. The main aims of this paper are therefore:

1. Develop a systematic tool (HARE) to plan and evaluate response during energy supply risk conditions.
2. Create an energy-supply-risk benchmark.
3. Show how such a tool can be integrated into existent medium-term planning systems in order to evaluate costs and benefits.
4. Demonstrate its use on a simplified example during the Chilean 2011-drought.
5. Draw first lessons on how the tool could be used for many different hydrothermal systems.

The remainder of this paper is organized in five sections. In Section "Introducing HARE: Measures and states of emergency and response" HARE, the proposed tool to analyze sustained energy crises, and its relevant definitions and information are presented. Section "Integrating HARE into hydrothermal coordination" describes the simplified mathematical model of the Chilean system used to demonstrate HARE. Section "Detailing HARE" describes HARE itself in detail, while Section "Case study" presents a simplified case study using the Chilean system at the beginning of 2011. Finally, Section "Conclusions" presents the conclusions and future work.

Introducing HARE: Measures and states of emergency and response

To use HARE (acronym in Spanish for *Herramienta de Análisis de Racionamiento Energético*, Energy Rationing Analysis Tool), the central planner needs to introduce two important elements to define its structure: an **analysis of measures** that can be applied to manage demand in times of medium-term shortages (both preventive and mandatory) and a **structure to benchmark the state of the system**, both in the mid/long-term perspective, in order to be able to start structuring the Staged Emergency Response.

The **structure of the benchmark** is defined as states through which the system can transit depending on a particular deficit index. The concept is derived from the state-diagram presented by Fink and Carlsen [3] for power systems' security analysis. The structure of the diagram follows the same principles and concepts established by the aforementioned authors, but instead of looking at the status of operational constraints, a generic energy shortage probability index is used along with associated thresholds for each state.

This index can be defined in several ways considering a variety of elements of the system in the long-run as presented in [4,7]. The index used in this work is the standard deficit probability applied as base case index in the latter references. It considers the results of the simulations of several hydrological scenarios to determine the statistical probability as the sum of cases with deficit over the total number of scenarios N_S (for each bus in every stage and block of demand). Consider the binary auxiliary variable $\delta(s,n,t,b)$, taking the value 1 if the system proves incapable of serving all energy demand in the hydrological scenario s at node n in stage t and block of demand b, and 0 otherwise. The *INDEX* for each node n, at stage t and block of demand b is calculated in (1).

$$INDEX(n,t,b) = \frac{1}{N_S}\sum_{s=1}^{N_S}\delta(s,n,t,b) \tag{1}$$

As a measure of reference to support the information given by *INDEX*, the maximum energy deficit for each bus in every stage and block of demand is determined for all the scenarios under analysis. No discount rate is used for the energy deficit evaluation over the time.

Considering the *INDEX*, it is possible to explain the state-diagram shown in Fig. 3. Basically, the structure considers Normal, Alert, Emergency, In Extremis and Restorative states, and the way to transit between states is almost identical to the original proposal, apart from the additional path between the Restorative to the Emergency state.

To set the system in a certain state, the central rule is to select the maximum value of the indexes obtained for the system in a 6 month period (following the criteria presented in [8] combined with the standard rationing enforcement period in Chile). This decision can be supported by additional information about the system's conditions, like the unserved energy (UE) for the worst case scenario among the hydrological sequences under analysis, the expected unserved energy, or any other measure of sustained energy/power shortage in the system.

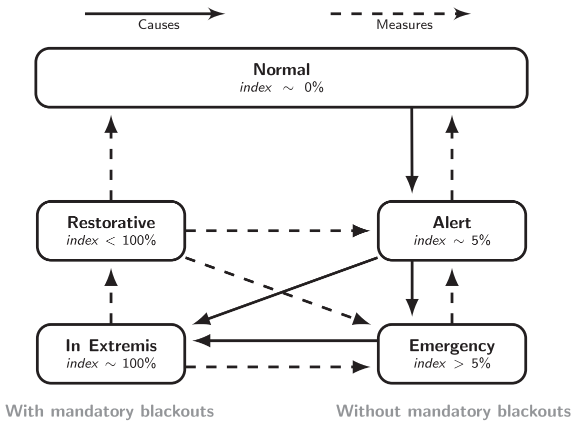

Fig. 3. Structure of the state diagram for a system in the long-run.

The desirable state is Normal, in which the *INDEX* is close to zero, thus showing a balanced system in the future. Using a threshold of 5% for the index, it is possible to define the Alert state. If the system is showing an increasing index over 5% (following the general criteria in [7]) the system is set in the Emergency state. It is important to underline that in the previous states, the situation is such, that no mandatory blackouts are necessary due to the capability of the system to solve the situation. If the index shows high certainty of deficit and blackouts are mandatory, the system is considered to be In Extremis. If the system is recovering and the index is declining but still showing high values, its state is said to be Restorative. Thresholds are flexible in order to properly represent the risk aversion of the evaluator (e.g. system operator, regulator), based on previous sustained shortage periods experienced by the system.

After defining the states and the index, it is necessary to understand the way a system transits through the states. As it can be appreciated in from Fig. 3, the paths between states are associated with causes and measures. To transit from a certain state to another one with a worse index, the causes presented in Section 'Introduction' must appear and persist, resulting in a deficit in one or more scenarios, leading to the associated higher index. Assuming that the causes are still present, the way back to a better state is achieved through the application of one or more measures.

Measures to overcome the deficit can include specific actions on the generation side, transmission networks, demand, etc. Since measures applied to the demand are the focus of this work, the actions we discuss and simulate are demand-side measures. A set of examples are presented in Table 1. There is an important trade-off between planning preventive and mandatory rationing measures (and the certainty of associated costs) and letting the system evolve naturally to a possible sustained scarcity scenario. When planning and imposing a staged emergency response, the regulator or system operator (as is the case in New Zealand) assumes the risk related to managing the situation, hence its necessity to evaluate what measures have most demand-side impact and least economic (and/or political) impact to effectively reduce the risk of crisis or its consequences.

Not every measure will have the same impact on the system in terms of energy reduction due to implementation timing and savings capability, and – at the same time – every measure will have a different degree of applicability due to costs of implementation. It is important to stress that the measures must be modeled as demand reductions, because the parameters and variables generally available in the mid-term model do not allow to explicitly model each measure (e.g. there are no voltages available in the model to represent the voltage reduction measure explicitly).

The measures are divided in four general categories, namely: price signal, temporary reduction, energy efficiency, and disconnection. For each measure several attributes are presented, including whether the measure helps reducing consumption and/or shifting it, the measure's impact on power and energy deficit, the delay between the enforcement of a measure and its implementation, and the corresponding costs identified. This last attribute is important since it is very difficult to actually include those associated costs in terms of effective monetary amounts for the optimality analysis, relegating its consideration to examination a posteriori in order to determine the impacts of using one particular measure.

It is necessary to emphasize that the previous measures do not consider the efforts that can be included at the generation or transmission level to help overcoming the energy constrained scenario,

Table 1
Example measures considered to manage demand [10,5,1].

Cat.	Measure	Reduce	Shift	E[a]	P[a]	Delay	Costs
Preventive and Mandatory Rationing							
Price signal	Quota system + Quota market + Price signal	yes		•	○	<2 months	Transaction
	Time-of-use		yes	–	•	Relative	Implementation
	Load shedding (Ancillary service)	yes		○	•	<1 day[b]	Market price
	Peak hour definition	yes	yes	○	•	Relative	Political/ productivity
Reduction	Daylight saving time extension		yes	○	•	Relative	–
	Extension/Addition of public holidays	yes		•	•	Weeks	Productivity
	Generator-consumer energy reduction agreement	yes		•	•	Relative	Transaction
	Overnight public events prohibition		yes	–	•	Relative	Political costs
	Public sector energy reduction	yes		•	○	Months	Implementation
	New loads: prohibition to enter	yes		•	•	Weeks	Productivity
	Supply voltage reduction	yes		•	○	<3 weeks	Equipment damage
EE[c]	Use of energy efficient equipment	yes		•	–	Months	Equipment replacement
	Energy efficiency plan	yes		•	–	Months	Implementation
Mandatory rationing							
Disconnection	Rolling blackouts	yes		•	•	< 1 day	UEC[d]/ Inefficient distribution/ Political
	Generalized overnight blackouts	yes		•	○	<1 day	UEC/ Political
	Restriction of energy intensive production lines at peak hours	yes	yes	○	•	weeks	Productivity

[a] E/P: Impact of the measure on Energy/Power (• high, ○ medium, - low/nothing).
[b] If the system already has the service.
[c] EE: Energy Efficiency.
[d] UEC: Unserved Energy Cost.

which leads to a worst case scenario analysis when only considering demand side measures.

Integrating HARE into hydrothermal coordination

To be able to evaluate the optimal set of measures in different states of the hydro-system, HARE needs to be integrated into the local medium-term hydrothermal scheduling model. In this paper, this is demonstrated on a simplified model used for the hydrothermal scheduling in Chile, following the standard principles for pricing the water stored in the reservoirs, through stochastic dual dynamic programming (SDDP) [13,14]. The model considers quadratic losses (see [12] for further discussion on related issues) for the economic dispatch sub-problem, which is solved using Sequential Quadratic Programming. The stochasticity is represented using historical inflow records to keep space and time correlations consistent [6].

The main feature of the change is the ability of the model to modify the energy demand (usually fixed) in every block of each stage of the problem as a result of the optimization of a corresponding demand variable for each load in the system. The structure of the mathematical formulation of the problem needs some detailed explanation. The model was used in [16] and its general structure and the necessary modifications are explained below.

The objective function (OF) is presented in (2), which considers all the costs associated with the operation at a specific stage t for a block of demand b, as well as the future costs expected at that moment, variable that is constrained by restriction associated with Eq. (9).

$$\min_{\overrightarrow{x}} \Phi^{t,b} = \sum_{i}^{N_{GT}} C_{TG_i} + \sum_{j}^{N_L} C_{UE_j} + \beta_q \sum_{k}^{N_I} q_{U_k} + \vartheta \tag{2}$$

$$\overrightarrow{x} = \left(\overrightarrow{p}, \overrightarrow{\theta}, \overrightarrow{q}, \overrightarrow{v}, \overrightarrow{\delta}, \vartheta\right) \tag{3}$$

The previous minimization is subject to the following constraints. The nodal power balances, described in (4), showing the demand variables δ_{L_j}.

$$\sum_{j\in\Omega_{G_i}} p_{G_j} + \sum_{j\in\Omega_{L_i}} p_{U_j} - \sum_{j\in\Omega_{BB_i}} p_{T_{ij}} - \sum_{j\in\Omega_{L_j}} \delta_{L_j} \geqslant 0 \qquad \forall i \in N_B \tag{4}$$

The model includes a global energy balance constraint (5) that allows to control (through the factor σ) the amount of energy reduction in relation to the energy demand expectation.

$$\sum_{i\in\Omega_{BB}} \sum_{j\in\Omega_{L_i}} \delta_{L_j} \geqslant \sigma \sum_{i\in\Omega_{BB}} \sum_{j\in\Omega_{L_i}} p_{L_j} \tag{5}$$

The power transfer through the transmission lines $p_{T_{ij}}$ are modeled using a DC load flow, whose upper and lower limits are shown in (6) and (7), respectively. The system is assumed to be represented in per unit, so the following relations can be easily extended to transformers.

$$(\theta_i - \theta_j) \leqslant x_{ij}\overline{f_{ij}} \qquad \forall (i,j) \in \Omega_{BB} \tag{6}$$

$$(\theta_i - \theta_j) \geqslant x_{ij}\underline{f_{ij}} \qquad \forall (i,j) \in \Omega_{BB} \tag{7}$$

The abovementioned constraints represent the power system constraints and they are relevant for the development of the methodology. All the relations related to hydraulic systems, like reservoir balance, power conversion at each hydraulic power plant, irrigation constraints are depicted in (8) (for details see [14]).

$$H \cdot \begin{pmatrix} \overrightarrow{p_H} \\ \overrightarrow{q} \\ \overrightarrow{v} \end{pmatrix} = \overrightarrow{b} \tag{8}$$

The future costs in the OF are constrained by the set of cuts yielded during the iteration of the optimization process, as expressed in Eq. (9). Those cuts build a polyhedral outer approximation of the future cost function for each stage, as described in greater detail in [9].

$$\vartheta \geqslant \vartheta_j\left(\overrightarrow{v}^{t,b}\right) \qquad \forall j \in \varphi \tag{9}$$

When it comes to the determination of the boundaries for each variable, there is an important consideration to make for the demand. Each load in the system is represented by a variable δ_{L_j}, which in turn is limited by factors of the expected load for that period, as presented in (10).

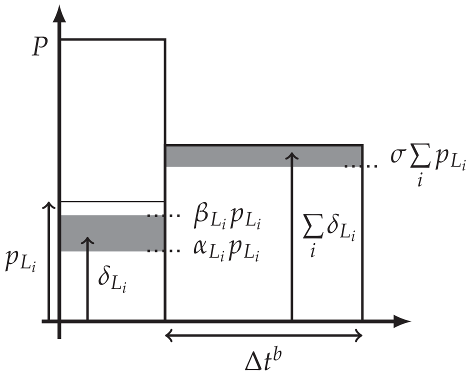

Fig. 4. Effects of the model for variable demand.

$$\alpha_{L_j}^{t,b} \cdot p_{L_j}^{t,b} \leqslant \delta_{L_j}^{t,b} \leqslant \beta_{L_j}^{t,b} \cdot p_{L_j}^{t,b} \qquad \forall j \in \Omega_L \tag{10}$$

The idea behind the previous expression is to model the effects of the measures on the different loads through the factors α (lower bound) and β (upper bound). Fig. 4 shows the interaction of the set of constraints (5) and (10) with the expected blocks of demand in each stage of the problem.

The remaining variables are limited by the usual constraints, summarized in (11) and (12).

$$\underline{\vec{y}} \leqslant \vec{y} \leqslant \overline{\vec{y}} \tag{11}$$

$$\vec{y} = \left(\vec{p}, \vec{\theta}, \vec{q}, \vec{v}\right) \tag{12}$$

With the elements presented in this section, it is possible to introduce the methodology that enables the analysis of measures on the demand to create strategies to face sustained deficit in power systems.

Detailing HARE

For the benefit of clarity, the explanation of the methodology is divided in 5 subsections: the definition of the problem, the initial calculation of the index (state classification), measures analysis and strategy proposals, strategy analysis, and selection. At the end of this section the practical application of the methodology is explained.

Problem definition

The definition of the problem requires gathering all the information about the system to generate the mid-term hydrothermal scheduling problem. A horizon of 2 years is selected to conduct the analysis, which involves knowing the future costs for the water stored in the reservoirs at the end of that period (through long-term hydrothermal scheduling). The basic information needed for the system analysis includes the expected demand, water inflows, generation cost functions, transmission system, hydraulic system, and unserved energy costs. Additionally, it is necessary to define both the optimization and simulation sequences to manage the uncertainty in water inflows.

Initial index and state assignment

By setting a value of 1 for all the factors α, β and the σ, one starts with a standard mid-term Hydrothermal Scheduling problem. Under this condition, it is possible to optimize and simulate the system in different hydrological scenarios to get the information about the expected operation of the system in each one of them; thereby, allowing to identify the data related to the unserved energy in every stage, making it possible to calculate the *INDEX* as described in Section "Introducing HARE: Measures and states of emergency and response". Considering the proposed index behavior, it is possible to define the state of the system in the mid-term.

Measures analysis and strategies

Table 1 shows several measures that could be applied on the demand side. It is necessary to estimate factors and to model the effect of each one of them on the different loads of the system, as well as the **identification of the costs and delays of implementation of the measures for the particular system under analysis at the specific moment of the evaluation**. This task is generally complex and needs to be conducted separately for each particular power system, since it requires gathering and analyzing large amounts of distinctive information. A systematic learning process regarding this approach is also envisioned.

Using the above information, it is possible to create sets of measures (a strategy) and to calculate factors α' and β' resulting from the interaction of the different measures considered in each strategy. The way this interaction is considered is a matter of estimation and experience. An interaction matrix (*IM*) can be defined, which considers the expected interaction of measures, allowing the calculation of resulting factors ($fr = 1 - \alpha$) through the following expression:

$$fr_p^{t,b} = 1 - \sum_{i \in \Omega_{S_p}} \left[\prod_{j \in \Omega_{S_p}} IM_{ij} \right] \left(1 - fr_i^{t,b} \right) \tag{13}$$

Eq. (13) describes the calculation of the reduction factors for stage t, block of demand b ($fr_p^{t,b}$) resulting from the aggregation of measures to create a demand side strategy p (Ω_{S_p}) during sustained energy crisis. It considers the reduction factors of each measure i ($fr_i^{t,b}$) included in the strategy in stage t, block of demand b, which is weighted by the effects of the interaction with the other measures in the strategy. The interaction with each of the other measures (represented by subscript j) is represented by an element of the interaction matrix IM_{ij}. This means that the resulting reduction factor for stage t, block of demand b is calculated by adding the real reduction of each measure, which in turn corresponds to the result of multiplying (product operator $\prod$) all the IM_{ij} factors associated to that measure, to weight the reduction factor of the measure acting isolated from the others. This means that the real effect of applying a measure might be penalized due to the existence of other measures acting at the same time.

For the sake of clarity, the calculation of reduction factors for a strategy is presented through a brief numerical example. Let's assume that there are three measures (with names a, b and c) available to set up a strategy X and that all the measures are used (i.e. $\Omega_{S_X} = \{a, b, c\}$). The interaction matrix for the set of measures is presented in (14).

$$IM = \begin{bmatrix} IM_{aa} & IM_{ab} & IM_{ac} \\ IM_{ba} & IM_{bb} & IM_{bc} \\ IM_{ca} & IM_{cb} & IM_{cc} \end{bmatrix} = \begin{bmatrix} 1 & 0.9 & 0.8 \\ 0.9 & 1 & 1 \\ 0.8 & 1 & 1 \end{bmatrix} \tag{14}$$

Additionally, the reduction factors considered in the example are $fr_a^{t,b} = 0.95, fr_b^{t,b} = 0.99$ and $fr_c^{t,b} = 0.98$, for any stage t and block b of demand. Following the structure defined in expression (13), the reduction factor for the strategy X for any stage t and block b

$$\begin{aligned} fr_X^{t,b} = 1 - \{ & (1 \cdot 0.9 \cdot 0.8) \cdot [1 - 0.95] + (0.9 \cdot 1 \cdot 1) \cdot [1 - 0.95] \\ & + (0.8 \cdot 1 \cdot 1) \cdot [1 - 0.98] \} = 1 - 0.061 = 0.939 \end{aligned}$$

After finding the resulting factors α' and β' for each plan, it is feasible to evaluate the impact of their application in terms to help the system return to a better state.

Strategy, indexes and selection

At this point it is clear that the application of the corresponding factors for each strategy will produce an output (*INDEX*) that allows the classification of the system in one of the States presented in Section "Introducing HARE: Measures and states of emergency and response". At the same time, it will be possible to sort the strategies – or at least discard some of them – through the consideration of the associated costs of implementation. This criteria of selections is chosen for practical reasons: the usual hurdle for the implementation of alert/emergency measures are the associated costs and delays of implementation, so this methodology better addresses the requirements of the evaluators behind the decision making process.

This inspection process should lead to the definition of an optimal set of measures to be applied to the demand in order to face that particular situation. Since the methodology only considers demand measures and no others to avoid the deficit (generation side, water management measures, etc.), this analysis can be understood as a worst case scenario; therefore, not losing generality.

Continuous operation

Since a power system operates continuously and it is permanently facing eventual periods of sustained deficit, it is necessary to structure the methodology in a suitable framework. In Fig. 5, it is possible to note the different steps to keep analyzing the system regularly. The diagram shows how the methodology operates practically, therefore it aims to show how the evaluator must proceed, and the time index t is not related with the time definition of the dynamic program (which is represented in the figure by the block *Model*). Suppose the system at a certain time, let's say $t = 0$, with all the necessary information for the mid-term evaluation. After optimizing and simulating the system for the hydrological scenarios, the index is calculated and the mid-term state of the system is defined (either *Normal* = 0, *Alert* = 1, *Emergency* = 2, *In Extremis* = 3 or *Restorative* = 4). If the state is *Normal*, then no further analysis is necessary until the next evaluation of the mid-term state of the system is performed (daily or weekly).

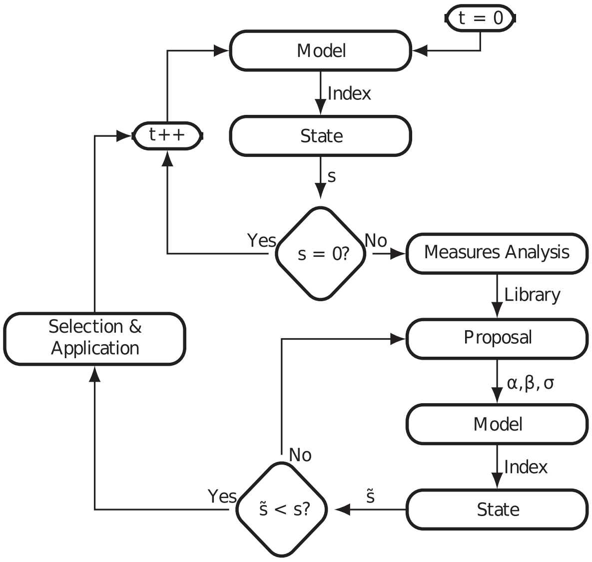

Fig. 5. Block diagram to explain the use of HARE in continuous operation.

In the event of observing a state different than Normal ($s > 0$), it is necessary to take the set of measures presented in Table 1 and to analyze the impact of each of them on the system in that particular condition. That includes (re) calculating the reduction factors α and β for each measure to reflect their actual effect on the system demand and assessing their independent impact on the total operation costs, generating the so called library of measures. After gathering all the information, it is possible to create proposals of groups of measures to face the expected deficit in the system. In this step, the decision maker can apply several filters to select the appropriate measures to fulfill the aforementioned objective. The groups of measures are combined considering (13) and tested on the model systematically, getting the necessary information to define the alternative state $\tilde{s}$ of the system. If state $\tilde{s}$ is better than state s, then the proposal qualifies as a possible alternative. When all alternatives are tested, the least cost plan (considering *non-monetary* costs) that overcomes all additional filters can be selected and applied to the system. The system continues its operation with periodical calculations of the index.

Case study

As a case study to apply the proposed methodology, we analyze the situation in Chile at the beginning of year 2011, when the government enforced a preventative rationing period for the SIC. This decision had two main justifications: (1) transmission constraints with adequacy consequences and (2) hydro resources scarcity near the load center of the system, represented in Fig. 6 by buses *Cerro Navia* and *Alto Jahuel*. Bus *PolpaicoNorte* summarizes the northern part of the system, and bus *AncoaSur500* does the same for the southernmost section of it.

The aim is to approximate the situation considering t_0 equal to January 1st, 2011. The analysis horizon is two years with 24 monthly stages, to follow the structure of the daily long term analysis conducted by the Chilean system operator. Since the regulation of the reservoirs in the system is intra-annual and considering a polyhedral approximation of the future costs for the 24th stage coming from a study considering a longer horizon (e.g. 10 years), all the necessary information is available to precisely represent energy availability in the system. Information about generators, demand blocks, transmission parameters, watershed topologies, and hydrology was obtained from the public records[3] published by the regulator (CNE, National Electricity Commission). The hydrology considers 51 hydrological years to build the sequences to conduct the optimization and the simulation of the system. The optimization process considers 3 sequences with 4 openings per stage to capture the essence of the stochastic problem (yearly historical data was used both for forward sequences and backward openings following a high-medium–low inflow pattern; low 1968 and 1998; medium 1966 and 1969; high 1972 and 1982), while the simulation process considers 100 sequences without openings (considering 50 different sequences of two consecutive years and 50 of two mixed years).

The problem was solved using the optimization platform CPLEX 10.2 on a processor Intel I5 @ 3.33 GHz. The process of getting the index, that means, optimizing 3 sequences and simulating 100 sequences, took about 35 min.

Initial index and state assignment

After obtaining all the data about the system in the 2 years horizon, it is possible to calculate the *INDEX* for each busbar in the

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[3] http://www.cne.cl/tarificacion/electricidad/precios-de-nudo-de-corto-plazo (accessed on April 2013).

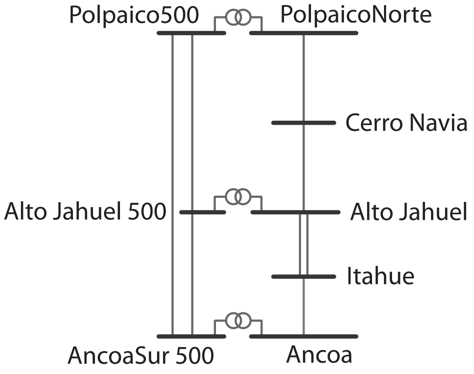


Fig. 6. Diagram of the SIC used as case study.

Table 2
Example of measures considered for the case study.

Id.	Measure	Delay	$1-\alpha$ (%)[a]	Δ*Costs* (%)[b]	INDEX
M1	Peak hour definition	March 2011	1.5	−0.221	7
M2	Load shedding (ancillary service)	3 weeks	2.6	−2.124	1
M3	Addition of public holidays	4 weeks	0.52	−0.217	3
M4	Generator-consumer energy reduction agreement	3 weeks	0.54	−0.247	5
M5	Public sector energy reduction	1 month	0.04–0.26	−0.042	7
M6	New loads: prohibition to enter (February–March)	3 weeks	0.12 & 0.23	−0.068	5
M7	Supply voltage reduction [17]	3 weeks	3.2	−2.626	1
M8	Energy efficiency plan	1 month	0.22	−0.69	5
M9	Restriction of energy intensive production lines at *peak* hours	3 weeks	0.72	−0.061	7

[a] The reduction value estimated for each measure corresponds to a specific analysis of data from different chilean sources and expert opinion.

[b] These costs are reduced total operation costs due to reduced demand. They are not the costs to society of such measures.

system. It is observed that the affected nodes are *Cerro Navia* and to a lesser extent, *Alto Jahuel*. In Fig. 7 the results for *Alto Jahuel* and *Cerro Navia* are presented for the first 12 months (monthly stages, two markers per month representing 2 blocks of demand); on the left side axis, the *INDEX* for the busbar, while on the right side axis the maximum degree of unserved energy for the analyzed scenarios.

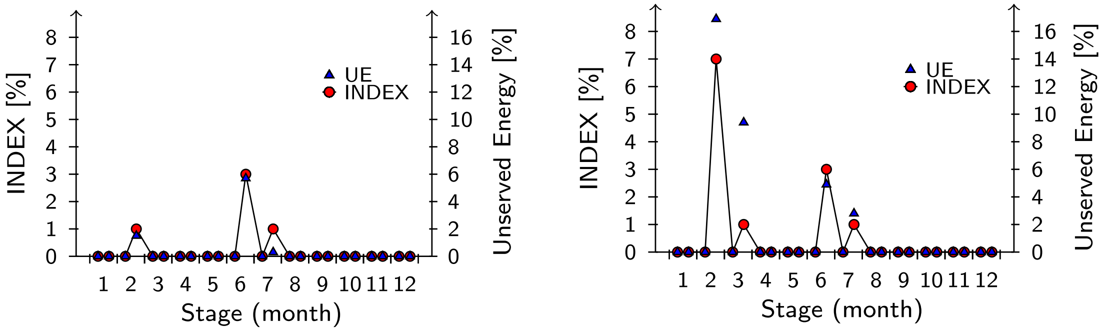
Depending on the type of deficit experienced by the system, it can be more convenient to analyze the weighted average of the *INDEX* in every busbar, instead of just a specific zone of the system. Since this particular case study presents problems in a confined part of the system because of local water scarcity and transmission constraints, the way to deal with it is to analyze the corresponding busbar, in this case *Cerro Navia*, based on Fig. 7b.

Considering the first 6 months (usual enforcement period of rationing measures in Chile), it can be concluded that the system can be placed in the Alert state, due to the 7% index in that time frame and the important amount of unserved energy if the worst hydrology arises.

Measures analysis and strategies

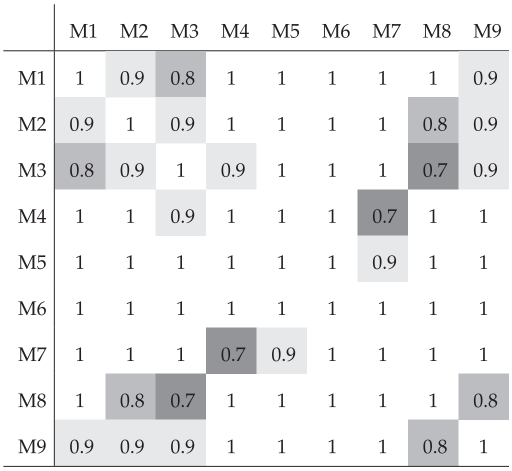
Since the system is in *Alert* state, the evaluator can discard some measures presented in Table 1 because they are not suitable for this kind of scenario, either because they are too expensive and/or difficult to implement, or because they focus on disconnection (undesirable unilateral action). Table 2 shows the subset of measures selected to analyze the situation and the complementary information obtained in the block *Measure Analysis* depicted in Fig. 5. The α factor and the delay are calculated *a priori* for every measure considering international and local experience as well as expert judgement. The *Measure Analysis* yields two results for each measure in the selected subset, namely the variation of costs (Δ*Costs*) and the index of deficit (*INDEX*). This information is calculated based on the operation information of the system using the scheduling model presented in Eqs. (2)–(12) when applying each measure on the system separately. This means that the reduction factor and delay of each measure is applied to the model through Eq. (10). The variation of costs considers the cost of the initial case as reference, which includes the operational cost, eventual unserved energy costs and expected future cost of the final stage, while the index of deficit (*INDEX*) is calculated through expression (1).

With the above information it becomes possible to build different strategy proposals to face the Alert situation. On behalf of conciseness, only 3 strategies will be analyzed and compared with the base case, namely M7 alone, the set M3–M4–M6–M7 (basic plan), and all measures acting together considering interaction through the IM presented in Fig. 8. The matrix is built based on expert judgement of the authors and collaborators about the nature of the interaction. It seeks to show how the interaction of measures impacts their effectiveness to reduce demand. It is important to note that each country must start their own learning process based on international experience in order to assess ex-ante the best combination (least cost/impact, maximum energy reduction) of measures for the different states of deficit in the long-term. This assessment can be articulated as a set of expert panels to discuss



(a) Alto Jahuel (b) Cerro Navia

Fig. 7. Initial INDEX and maximum unserved energy among simulation scenarios for critical busbars.



	M1	M2	M3	M4	M5	M6	M7	M8	M9
M1	1	0.9	0.8	1	1	1	1	1	0.9
M2	0.9	1	0.9	1	1	1	1	0.8	0.9
M3	0.8	0.9	1	0.9	1	1	1	0.7	0.9
M4	1	1	0.9	1	1	1	0.7	1	1
M5	1	1	1	1	1	1	0.9	1	1
M6	1	1	1	1	1	1	1	1	1
M7	1	1	1	0.7	0.9	1	1	1	1
M8	1	0.8	0.7	1	1	1	1	1	0.8
M9	0.9	0.9	0.9	1	1	1	1	0.8	1

Fig. 8. Example of the interaction matrix for the measures presented in Table 2.

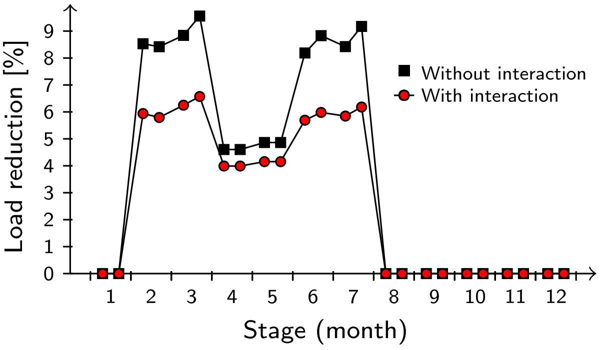


Fig. 9. Maximum load reduction at Cerro Navia busbar.

and determine the structure of measures to face energy shortage periods. Fig. 9 attempts to show the relevance of the adequate consideration of the interaction between measures in the context of the selection of strategies. The evaluator might be overestimating the load reduction up to 4% in a certain busbar if the interaction is not properly considered.

An important aspect to ponder is that every plan under analysis considers measure M7, so it is direct that the plan with less implementation costs is M7 alone, followed by the basic plan and finally all measures acting together. Since there are not only costs that can be quantified in monetary units, but qualitative characteristics, like the political burden/social impact associated to specific measures, in a real situation, a proper mixed analysis [11] must be applied to evaluate the costs of implementation.

In order to graphically conceptualize the impact of the different strategies under analysis, the maximum load reduction due to the different strategies at the critical bus (Cerro Navia) is presented in Fig. 10.

Strategy indexes and selection

Considering the aforementioned plans, next step contemplates the calculation of indexes and maximum unserved energy. The resulting operational cost reduction for all measures considered acting simultaneously is −4.36%, for the basic plan is −3.2%, and the voltage reduction measure −2.62% in regards to cost of the base case. The corresponding indexes are 0, 1 and 1. In Fig. 11, indexes (different than zero) and UE levels are plotted for the basic plan and the voltage reduction measure. The strategy consisting in

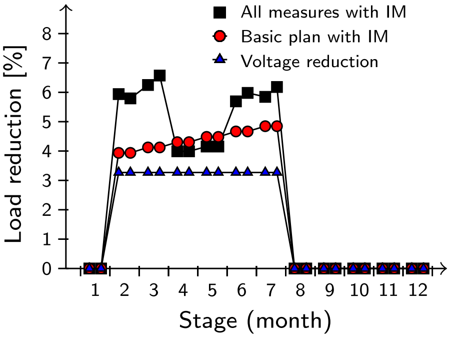


Fig. 10. Maximum load reduction at Cerro Navia busbar.

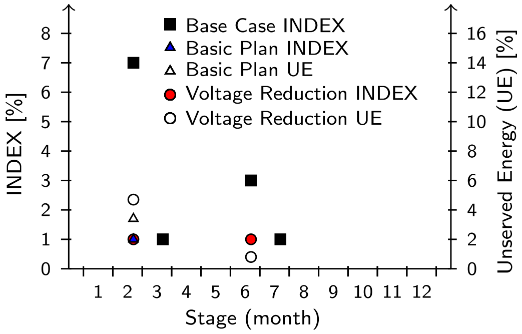


Fig. 11. Indexes and unserved energies for the main strategies.

all measures acting together, albeit successful in taking the index back to zero, has high implementation costs due to the inclusion of measures M2–M5–M9. Therefore, no further analysis is conducted in regard of that plan, considering the good results reached with the other alternatives at a lower cost.

Since the index of the basic plan is the same as the voltage reduction measure, and the corresponding maximum unserved energy in each case is about the same (around 2 [%]), it is straightforward that the best cost-effective strategy is to rely only on M7 to face the particular situation experienced by the system at that point. When it comes to consider the impact of adding public holidays (M3) and the prohibition to connect new loads (M6), it is clear that the reduction in costs - for this scenario of energy supply risk - are lower than the additional costs due to the lost of productivity (roughly evaluated in hundreds of millions of US dollars per day of implementation).

It is interesting to underline that the actual plan enforced by the regulator at that time only included that specific measure on the demand to manage the situation. However, in perspective, all rationing plans enforced in the history of the competitive market in Chile have included only that measure, in spite of being completely different situations.

Conclusions

The paper describes a novel methodology for systematic, transparent and efficient management - from a centralized point of view - of energy supply risk situations in power systems. A system state classification based on an objective estimation of the operational conditions is proposed. Additionally, a formal definition of a set of general measures that can be applied with their corresponding attributes is presented. The functionality of the approach is demonstrated on a simplified, but realistic situation of the Chilean power system experienced in year 2011. The results show that it is possible to define a set of measures that efficiently reduce the impacts on the system and to select a posteriori the one with less implementation costs.

Future developments will be focused on the inclusion of new feasible measures related with a more detailed cost-benefit analysis of each set of measures, the management of storage systems, irrigation agreements (associated social benefits of water management), and security based transmission constraints. Additional work is envisioned in the area of social welfare analysis through the resulting prices after the application of the proposed strategies. This aims to complement the implementation cost analysis for strategy selection, as well as to focus on the quantification of the social impact of lost load.

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References

[1] Bryan S. Saving electricity in a hurry. Tech. rep., International Energy Agency; 2011.

[2] Carreno E, Sanchez T, Padilha-Feltrin A. Consumer behavior after the brazilian power rationing in 2001. In: Transmission distribution conference and exposition: Latin America; 2006. p 1 – 6.

[3] Fink LH, Carlsen K. Operating under stress and strain. IEEE Spectrum 1978;15:48–53.

[4] Galetovic A, Munoz CM. Estimating deficit probabilities with price-responsive demand in contract-based electricity markets. Energy Policy 2009;37(2):560–9.

[5] Heffner G, Maurer L, Sarkar A, Wang X. Minding the gap: World bank's assistance to power shortage mitigation in the developing world. Energy 2010;35(4):1584–91.

[6] Helseth A, Mo B, Warland G. Long-term scheduling of hydro-thermal power systems using scenario fans. Energy Syst 2010;1(4):377–91.

[7] Kelman R, Bezerra BV, Rosenblat J, Pereira M, Pinto A, Barroso L. Calculation method of rationing determination probablitiy. In: SNPTEE, Seminário Nacional de Producao e Transmissao de Energia Elétrica; 2007.

[8] Marcato A, Mendes A, Iung A, Cesar T, Barros M, Souza R, et al. Incorporation of rationing effects to hydrothermal dispatch optimization. In: PowerTech IEEE Bucharest; 2009. p 1 – 8.

[9] de Matos V, Philpott A, Finardi E. Improving the performance of stochastic dual dynamic programming. Optim Online 2012.

[10] Maurer L, Pereira M, Rosenblatt J. Implementing power rationing in a sensible way: lessons learned and international best practices. Report 305, ESMAP, Energy Sector Management Assistance Program; 2005.

[11] Pacheco J, Contreras E. Manual metodológico de evaluación multicriterio para programas y proyectos; 2008.

[12] Palma-Benhke R, Philpott A, Jofré A, Cortés-Carmona M. Modelling network constrained economic dispatch problems. Optim Eng 2012:1–14.

[13] Pereira MVF, Pinto LMVG. Multi-stage stochastic optimization applied to energy planning. Math Program 1991;52:359–75.

[14] Pereira MVF, Campodónico N, Kelman R. Long term hydro scheduling based on stochastic models. Proceedings of EPSOM 98; 1998.

[15] Transpower. Emergency management policy. URL http://www.systemoperator.co.nz/emp; 2013 [accessed April 2013].

[16] Vargas LS, Palma R, Moya O, Torres R. A scenario simulation approach for market power analysis in hydrothermal systems. Power Eng Rev, IEEE 2002;22(8):65.

[17] Vinnal T, Kutt L, Kalda H. Analysis of power consumption and losses in relation to supply voltage levels. In: Power quality and supply reliability conference; 2008. p 23 – 8.