Ann Oper Res (2019) 274:101–117
https://doi.org/10.1007/s10479-018-2920-1

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OR MODELING/CASE STUDY

Energy technology environment model with smart grid and robust nodal electricity prices

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Published online: 6 June 2018

Abstract This paper deals with the modeling of power flow in a transmission grid within the multi-sectoral multi-energy long-term regional energy model ETEM-SG. This extension of the model allows a better representation of demand response for flexible loads triggered by nodal marginal cost pricing. To keep the global model in the realm of linear programming one uses a linearized DC power flow model that represents the transmission grid with the main constraints on the power flowing through the different arcs of the electricity transmission network. Robust optimization is used to take into account the uncertainty on the capacity limits resulting from inter-regional transit. A numerical illustration is carried out for a data set corresponding roughly to the Leman Arc region.

Keywords OR in energy · Long-term energy model · Power flow · Robust nodal electricity prices · Robust optimization

1 Introduction

The transition to sustainable energy system in Europe as in the rest of OECD countries involves an increase of distributed power generation from variable renewable sources such as wind turbines and solar panels, the development of electric mobility, the linking of power and heat or cooling generation and the active use of demand response. ETEM-SG (Energy/Technology/Environment/Model with Smart-Grids) that we use on this research is a model developed recently (Babonneau et al. 2012; ORDECSYS 2014) to assess the future role of renewable and smart-grid technologies in the energy transition at a regional level. It

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belongs to the TIMES family of models (Loulou and Labriet 2008), which represents the optimal capacity expansion in production technology and the flow of resources in the whole energy system of a region, a country or a group of countries. These models are well-known to lead to large-scale mathematical formulation and, as such, extensions to power flow and uncertainty modeling bring numerical issues and challenges. In Babonneau et al. (2016), ETEM-SG has been extended to model distribution network characteristics, and market clearing processes for flexible load and distributed energy resources providing reserve and reactive power compensation. Each distribution grid emanating from a bus was summarized by a single line on which the distributed energy resources were connected. An alternative current (AC) formulation was adopted to take into account reactive power compensation. The resulting nonlinear model was solved through successive linearization in a Gauss Seidel iterative procedure.

In this paper one presents a new extension of the multi-sectoral multi-energy long-term regional energy model ETEM-SG permitting a robust representation of power flow constraints in the regional transmission grid. This extension is needed because, in ETEM-SG, demand response is modeled as an optimal response of flexible loads and distributed energy resources to time of use pricing schemes based on marginal cost. Since the loads and the generation units are geographically distributed these prices should be represented by nodal marginal costs associated with a representation of the transmission grid. A linearized DC equivalent power flow model which is justified under an assumption of low resistance and high susceptance of the lines, an assumption often made in the modeling of power systems is now included in ETEM-SG. It provides a representation of the transmission grid with the main constraints on the power flowing through the different arcs of the electricity transmission network. The scenarios obtained through running ETEM-SG will thus propose for each timeslice an optimal dispatch of production units of the regional energy system with demand response activities triggered by marginal cost pricing and at a larger time scale the optimal location and timing of new capacities introduction for power generation (in particular the technologies based on renewable sources), the development of distributed storage [e.g., through electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs)] and the investment in network reinforcement. Because we aim to focus on the impact of introducing robust nodal pricing in a regional energy model, we have simplified the description of the distribution constraints and options, eliminating in particular reactive power compensation considerations. This has the merit to keep the whole model within the linear programming realm.

Because the power flows circulating in a regional transmission grid depend on what happens on the transmission grid for a much larger perimeter, a robust optimization (RO) technique (Babonneau et al. 2010; Ben-Tal et al. 2009) is introduced to take into account the resulting uncertainty on the capacity limits for the different arcs of the regional transmission grid. RO is an alternative to classical approaches (e.g., Stochastic Programming, Chance Constraint Programming) that aims at overcoming numerical issues induced by calculus of probability and by the well-known curse of dimensionality. The main idea of RO is to start with a non-probabilistic formulation of uncertainty, namely the uncertainty set, and look for solutions that remain satisfactory for all possible realizations in the uncertainty set. Solutions having this property are named robust. As no probability model is assigned to the uncertainty computing robust solution becomes a numerically tractable operation. The paradigm of robust linear optimization goes back to Soyster (1973) and it has been revived in the nineties by El-Ghaoui and Lebret (1997) and by Ben-Tal and Nemirovski (1998). Recently it has been applied to long-term energy models to cope with different sources of uncertainties. In Babonneau et al. (2010), the authors combined RO with Stochastic Programming in a power supply model under pollution constraints with uncertainties on demands and pollutants

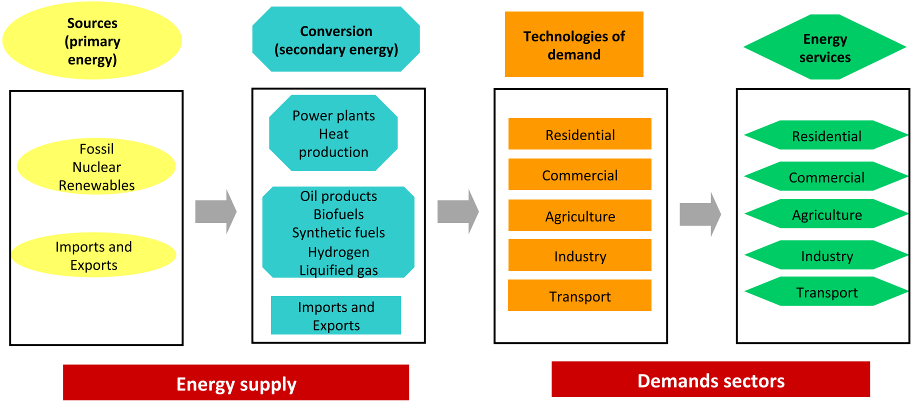

Fig. 1 Reference energy system

diffusion coefficients. Energy security of EU is analysed in Babonneau et al. (2012) using the long-term TIAM-WORLD model in which energy supply routes are subject to random events. In Andrey et al. (2015), RO is also applied to deal with uncertainty related to the impacts of climate change on the evolution of regional energy systems.

The paper is organized as follows. In Sect. 2 one gives a brief presentation of the multi-sectoral multi-energy long-term investment planning tool ETEM-SG. In Sect. 3 one describes the linearized DC power flow model to be introduced in ETEM-SG and one addresses the implementation issues. Section 4 is devoted to the robust optimization approach to deal with uncertain power flow transits. In Sect. 5 a numerical illustration is provided and finally in Sect. 6 we concludes.

2 ETEM-SG in short

A complete description of the ETEM-SG model is provided in Babonneau et al. (2017). ETEM-SG is a linear programming model, related to the TIMES family of models (Berger et al. 1992; Fragnière and Haurie 1996; Loulou and Labriet 2008), which represents the optimal capacity expansion in production technology and the flow of resources in the whole energy system. ETEM-SG is a multi-sectoral multi-energy technology rich model (See Fig. 1) specifically designed to analyze energy transition at regional level.

In its standard version the model is driven by exogenously defined useful energy demands that is the demand for energy services and imported energy prices. All technologies are defined as resource transformers and are characterized by technical coefficients describing input and output, efficiency, capacity bounds, date of availability (for new technologies), life duration, etc. Economic parameters define investment, operation and maintenance costs for each technology. The planning horizon is generally long enough to offer a possibility for the energy system to have a complete investment technology mix turnover.

Typically ETEM simulates the development of an efficient regional energy system with a planning horizon of 30–50 years usually divided in periods $t \in T$ of 1–5 years (5 years in the simulations). In each period one considers a few typical days (e.g., 6 days corresponding to the three seasons—Winter, Summer, Spring-Fall—and a user-defined day structure using timeslices such as, for example, a peak and a non-peak part of a day—). Each of these days is subdivided into groups of hours to obtain finally a set of timeslices $s \in S$ that will be used to represent load curves, distribution of demand and resource availability in different seasons and at different time of the day. This time structure is particularly important to represent correctly demands dynamics and the way one can exploit their flexibility. This mechanism is known as demand-response. The definition of timeslices in ETEM-SG should allow a representation through state equations of the dynamics of the energy services required during a day, e.g., maintaining a comfort zone in residential heat and recharging EVs and PHEVs.

3 Modeling optimal power flows in ETEM-SG

In this section one shows how to integrate a linearized DC power flow sub-model within the whole energy model ETEM-SG. For a detailed description of power flow modeling the reader is referred to Bacher (1992).

3.1 Linearized load flow model

Consider a transmission network with N nodes (or buses) linked by L lines described by the following variables and parameters:

- y_n: net power injection at node $n = 1, \dots, N$; $\mathbf{y}$ is the N vector with elements y_n.
- z_ℓ: flow along line $\ell = 1, \dots, L$; $\mathbf{z}$ is the L vector with elements z_ℓ.
- $\bar{A}$: network incidence matrix $L \times N$, with $a_{\ell,n} = 1$ if line ℓ originates from n, $a_{\ell,n} = -1$ if line ℓ terminates on n, $a_{\ell,n} = 0$ otherwise. Note that the sum of the columns of A is always equal to the the null column.
- A: an $L \times (N-1)$ matrix obtained by removing a column corresponding to the *swing bus*.[1] in the matrix $\bar{A}$.
- $\mathbf{S}$: an $L \times L$ diagonal matrix, $\mathbf{S} = \text{diag}(\mathbf{S}_1, \dots, \mathbf{S}_L)$, where $\mathbf{S}_l$ is the susceptances.[2] vector of line l.

The linearized Power Flow equation can be written as

$$\mathbf{z} = \mathbf{S}A\theta \tag{1}$$

where θ is the $(N-1)$-vector of angles at the different nodes (buses). Since $\mathbf{y} = A^T\mathbf{z}$, and by introducing A^TSA, one gets:

$$\mathbf{z} = \mathbf{S}A(A^T\mathbf{S}A)^{-1}\mathbf{y} \tag{2}$$

which can be rewritten

$$\mathbf{z} = \Psi\mathbf{y} \tag{3}$$

where Ψ is now called the injection shift factor matrix.

[1] Usually the swing bus is numbered 1 for the load flow studies. This bus sets the angular reference for all the other buses. Since it is the angle difference between two voltage sources that dictates the real and reactive power flow between them, the particular angle of the swing bus is not important.

[2] In electrical engineering, susceptance (**B**) is the imaginary part of admittance. The inverse of admittance is impedance and the real part of admittance is conductance. In SI units, susceptance is measured in siemens.

3.2 The optimal dispatch problem and its dual solution

Assume that an accurate description of the transmission grid is obtained by using a linearized DC load flow model and neglecting losses on the lines. The nodal prices can be obtained from the dual solution of an optimal dispatch problem under constraints of capacity of the generators and transmission network as shown by Ruiz et al. (2011, 2012a, b) or Stiel (2011).

The distribution of power in the different lines of the transmission network is given by Eq. (2) which we rewrite as follows

$$P_f = \Psi(P_{Gen} - P_{Load}) \tag{4}$$

where $P_f = \mathbf{z}$ is the vector of power flows on each line of the network and $P_{Gen} - P_{Load} = \mathbf{y}$ is the vector of net power injection (generation power P_{Gen} minus load P_{Load}) at each bus (node) of the network. The *transmission sensitivity matrix* $\Psi = \mathbf{S}A(A^T\mathbf{S}A)^{-1}$, also known as the *injection shift factor matrix*, gives the variations in flows due to changes in the nodal injections. The shift factor matrix is a function of the characteristics of the transmission elements and of the state of the transmission switches. For a given point in time, the system operator dispatches the committed units so as to minimize the total costs of operations. Assume that the generation costs are piecewise linear and denote the vector of nodal generation annualized costs[3] by c_{Gen}.

The economic dispatch is formulated as the following linear program:

$$\min_{P_{Gen}} c_{Gen}^T P_{Gen} \tag{5}$$

under the following set of constraints (with the associated dual variables indicated in the RHS):

$$\mathbf{1}_N^T(P_{Gen} - P_{Load}) = 0 \qquad (\lambda) \tag{6}$$

$$P_{f\,\min} \leq \Psi\,(P_{Gen} - P_{Load})_- \leq P_{f\,\max} \qquad (\mu_{\min}, \mu_{\max}) \tag{7}$$

$$P_{Gen}^{lo} \leq P_{Gen} \leq P_{Gen}^{up} \qquad (\gamma_{\min}, \gamma_{\max}) \tag{8}$$

where $\mathbf{1}_N$ stands for an N vector whose components are all equal to 1. The constraint (6) ensures the total load-generation balance, (7) enforces the flow limits on transmission elements and flowgates where lower limits usually represent the limit in the opposite flow direction, and (8) models the lower and upper generation limits. In Ruiz et al. (2011) it is shown that the nodal marginal prices is then given by

$$\pi = -(\lambda\,\mathbf{1} + \Psi^T(\mu_{\max} - \mu_{\min})). \tag{9}$$

One must now integrate this optimal dispatch model in a multi-energy long term LP model like ETEM-SG (Babonneau et al. 2012). The implicit nodal prices given by expressions similar to (9) in this larger model will then serve to guide demand response, e.g., in charging of EVs or PHEVs and the use of these technologies for distributed storage.

3.3 Introduction of a transmission grid sub-model in ETEM-SG

The optimal dispatch equations (with a proper representation of the power transmission grid) are introduced in the ETEM-SG equations at the finest level of time scale and geographical information.

[3] Expressed in \$/MWh or CHF/MWh.

Time scale representation: The dispatch problem is to be solved explicitly in ETEM-SG for every timeslice $s \in S$ and all periods $t \in T$ under regular and peak load conditions. Power flows on the transmission grid are thus computed for all timeslices.

Geographical decomposition: Because the transmission grid defines some important constraints in the dispatch problem, it is necessary to decompose the regional energy system represented in ETEM-SG in subregions $n \in N$, each one corresponding to a node of the transmission grid. Useful demands are defined for each subregion separately and ETEM-SG will thus determine a complete energy sub-system at each node of the grid, describing in particular, electricity production units and technologies generating an electricity demand. Then electricity generation (injections) and loads are computed at each node for each timeslice and used to determine the resulting power flow.

Power flow equations in ETEM-SG: The new equations introduced in ETEM-SG and the link with existing variables and constraints are described here: Let N be the set of subregions represented in ETEM-SG and $\bar{L}$ the number of pairs of subregions that are connected and that may directly exchange electricity. Note that $\bar{L} \leq L$, L being the number of transmission lines, as two connected subregions can be linked by multiple line transmissions. In the standard ETEM-SG formulation, there is a variable, denoted $Exchange[t, s, n_1, n_2]$, that represents the electricity energy exchanged between subregions $n_1 \in N$ and $n_2 \in N$ in period t and timeslice s. A positive number means electricity goes from n_1 to n_2 while a negative one means the opposite.

The following new equation constraints link power flow variables with the electricity exchanges:

$$Exchange[t, s, n_1, n_2] = \alpha^s \sum_{l \in L_{n_1,n_2}} z_l^{t,s}, \quad \forall\, t \in T,\ \forall\, s \in S,\ \forall\, n_1 \in N,\ \forall\, n_2 \in N \tag{10}$$

where $L_{n_1,n_2} \subset L$ is the subset of arcs between n_1 and n_2, $z_l^{t,s}$ is the power flowing from n_1 to n_2 (or from n_2 to n_1 if negative) at period t and timeslice s and α^s is a coefficient to convert energy to power.

Each power flow is constrained by line capacities c

$$-c_l^t \leq z_l^{t,s} \leq c_l^t, \quad \forall\, t \in T,\ \forall\, s \in S,\ \forall\, l \in L. \tag{11}$$

Finally power flows are defined from Eq. (1):

$$z_l^{t,s} = (\theta_{n_1}^{t,s} - \theta_{n_2}^{t,s}) s_l, \quad \forall\, t \in T,\ \forall\, s \in S,\ \forall\, l \in L \tag{12}$$

where θ are variables representing bus angles at transmission nodes and s_l is the susceptance factor of line l.

4 Robust optimization to deal with uncertain power flow transits

The power flowing through a regional transmission grid depends on regional activity but also on what happens on the transmission grid on a much larger perimeter due to power flow transits. When dealing with long-term analysis, these activities are uncertain but have an impact on regional network congestion. An approach for simulating these power flow transits would consist in using flow estimates from a model representing the aforementioned larger perimeter. Without a proper access to this information, it is proposed here the use a robust optimization approach to take into account the resulting uncertainty on the capacity limits for the different arcs of the regional transmission grid.

In so doing, the randomness of the situation is formulated broadly. In other words, one does not model uncertain capacity on each transmission line separately but, instead, the entire set of lines is considered simultaneously when assessing the risk. This is justified by the fact that the modeler is not interested in knowing exactly what happens on each individual line but, rather, in defining power flows that may satisfy regional loads and injections at nodes at all timeslices and for all possible conditions of lines saturation.

One therefore creates aggregate capacity constraints by summing at each timeslice $s \in S$ and period $t \in T$ the $|L|$ constraints (11) to obtain:

$$-\sum_{l\in L} \beta_l^t c_l^t \le \sum_{l\in L} z_l^{t,s} \le \sum_{l\in L} \beta_l^t c_l^t, \quad \forall\, t \in T,\ \forall\, s \in S \tag{13}$$

where β_l^t are random factor with values in [0, 1]. For the sake of simpler notations the time indices s and t are omitted in the following equations.

4.1 Uncertainty model

Define the random coefficients β_l as follows

$$\beta_l = \bar{\beta}_l - \hat{\beta}_l \xi_l \tag{14}$$

where $\bar{\beta}_l$ represents the nominal congestion rate of transmission line l resulting from power transits, $\hat{\beta}_l$ the congestion variability and ξ is a set of independent random variables with support $[-1, 1]$. Using this definition, the capacity of line l available locally takes values in $[c_l(\bar{\beta}_l - \hat{\beta}_l); c_l(\bar{\beta}_l + \hat{\beta}_l)]$. Equation (13) becomes:

$$-\sum_{l\in L} (\bar{\beta}_l - \hat{\beta}_l \xi_l) c_l \le \sum_{l\in L} z_l \le \sum_{l\in L} (\bar{\beta}_l - \hat{\beta}_l \xi_l) c_l \tag{15}$$

which can be written differently as:

$$\sum_{l\in L} (\bar{\beta}_l c_l + z_l) - \sum_{l\in L} \hat{\beta}_l \xi_l c_l \ge 0 \tag{16a}$$

$$\sum_{l\in L} (\bar{\beta}_l c_l - z_l) - \sum_{l\in L} \hat{\beta}_l \xi_l c_l \ge 0 \tag{16b}$$

where the first summations of two constraints are linear deterministic expressions whereas the second summations represent random terms.

4.2 Robust optimization for ETEM-SG

One applies Robust Optimization method (Ben-Tal et al. 2009) to (16a) and (16b). Although constraints are immunized separately in the Robust Optimization paradigm, it has been showed in Babonneau et al. (2010, 2013) that two-sided inequality constraints such as (16a) and (16b) can be treated simultaneously.

One considers an uncertainty set defined as follows

$$\Xi = \left\{ \xi \in \mathbb{R} \mid -1 \le \xi_l \le 1 \text{ and } \sum_{l\in L} \xi_l \le k \right\} \tag{17}$$

in which k represents the immunization factor. Using robust optimization techniques, the worst case situation for network saturation is given by the robust equivalent of the robust constraints (16a) and (16b)

$$\sum_{l\in L}(\bar{\beta}_l c_l + z_l) - k||\hat{\beta}_l c_l - w||_\infty - ||w||_1 \geq 0 \tag{18a}$$

$$\sum_{l\in L}(\bar{\beta}_l c_l - z_l) - k||\hat{\beta}_l c_l - w||_\infty - ||w||_1 \geq 0 \tag{18b}$$

which is equivalent to the system of linear inequalities

$$\sum_{l\in L}(\bar{\beta}_l c_l + z_l) - \sum_{l\in L} u_l - kv \geq 0 \tag{19a}$$

$$\sum_{l\in L}(\bar{\beta}_l c_l - z_l) - \sum_{l\in L} u_l - kv \geq 0 \tag{19b}$$

$$u_l + v \geq \hat{\beta}_l c_l, \quad \forall\, l \in L \tag{19c}$$

with additional variables u, v and w.

From (Ben-Tal et al. 2009), one can derive a satisfaction probability for capacity constraints for any realization of $\xi \in \Xi$ that depends on the radius k of the uncertainty set. This result is given in Proposition 1. The factor k plays a crucial role as the larger its value, the greater the number of realizations ξ that are considered.

Proposition 1 *Let ξ_i, $i = 1, \ldots, n$ be independent random variables with values in interval $[-1, 1]$ and with expected value zero: $E(\xi_i) = 0$. Then, for all $k \geq 0$*

$$Prob\left\{\xi \in \Xi \mid \textstyle\sum_{l\in L} \hat{\beta}_l \xi_l c_l > k||\hat{\beta}_l c_l - w||_\infty\right\} \leq \exp(-\tfrac{k^2}{2.5|L|}). \tag{20}$$

In the numerical experiment presented in Sect. 5, one considers a transmission network with 12 lines (i.e., $|L| = 12$) and one sets $k = 10$. This leads to a 96% constraint satisfaction probability.

5 Numerical illustration

In this section one provides an illustration of the model using a case study, which corresponds broadly to the regional energy system of the "Léman Arc" area in Switzerland (Cantons of Vaud and of Geneva). Note that the objective of this numerical simulation is to illustrate the impact of introducing a representation of power flow constraints and robustness in a regional energy model, and not to provide a precise representation of the energy policy choices in this region.

The energy model is adapted from an ETEM-SG model that had been developed in previous projects[4] in which three subregions were represented. This spatial decomposition corresponds, globally, to the three power distribution companies operating in the region (i.e., *SIG* for Geneva, *SIL* for Lausanne and *Romande Energie (ROM)* for the rest of the region) but it does not match any grid transmission aspect. One explains below how the regional energy system has been reorganized into 9 subsystems connected through power transmission lines. The ETEM-SG simulations are performed for a 2015–2050 horizon planning with 5-year periods decomposition.

[4] The reader is referred to the RITES (ORDECSYS 2013) and TOU (ORDECSYS 2014) projects, which were supported by the Swiss Federal Office of Energy.

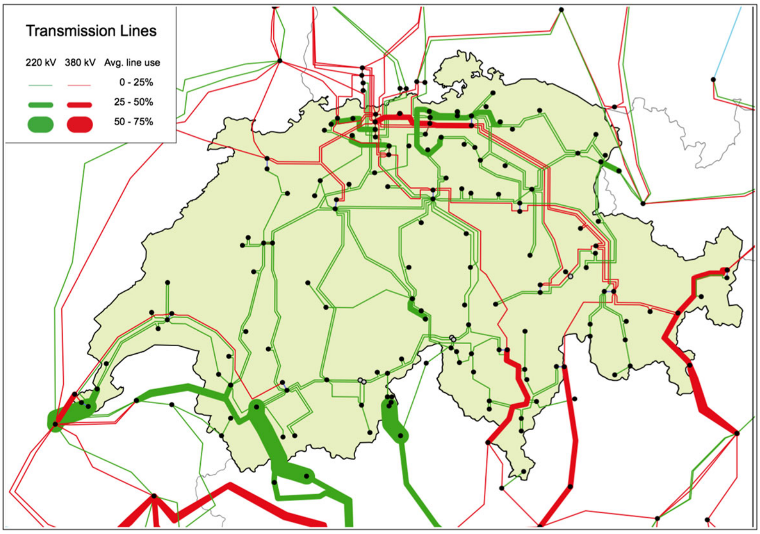

Fig. 2 Swiss transmission grid in 2015 (Figure from Weigt and Schlecht 2014)

5.1 Data

Energy system of Lac Léman area: In 2010, the total annual energy consumption of the "Léman Arc" region was 114.3 PJ and, overall, CO_2-eq emissions amounted to 5.48 Mt. The region is a net importer of electricity, around 5.5 TWh out of a total electricity consumption of 7.1 TWh in year 2010.[5]

Transmission grid: Figure 2 shows the Swiss transmission grid as reported in Weigt and Schlecht (2014). The network used in the ETEM-SG model will be a subgraph of this network, i.e., the one corresponding to the bottom-left corner. From the description of the Swiss transmission grid one can extract the sub-grid involved in the "Léman Arc" area. It is schematically represented in the Figures of resuls 7 and 8 with 9 nodes each one connected to a local energy subsystem and 12 transmission lines. Among the 9 nodes, three (Verboix, Romanel and Triphon) are connected to the Swiss and European transmission grid for electricity import/export and transit. Line capacities and reactances are set to values used in Weigt and Schlecht (2014).

Useful demands: Table 1 gives the regional useful demands considered in the case study and Fig. 3 displays their assumed evolution up to 2050. For the present exercise, demands are distributed geographically among the 9 subsystems connected to the transmission grid. The allocation of demand to nodes is obtained by first satisfying the observed demands for the three power distribution companies in the three main areas (Geneva, Lausanne and the rest of the region) and then by distributing uniformly the demand to the buses located in the considered areas (2 buses for Geneva, 2 buses for Lausanne and 5 buses for the rest of the region).

Finally demands are distributed on a yearly basis, among the 12 timeslices defined, for three seasons (Winter, Summer, Intermediate), and four parts of Day (Night, morning peak P1, Mid-Day and evening peak P2), as illustrated in Fig. 4.

[5] For more details on the global energy system, the reader is referred to ORDECSYS (2013, 2014).

Table 1 Useful demands classification (PJ means PetaJoules and tkmv/d means thousands kms vehicle per day)

Sector	Label	Code	Unit
Residential	Heat existing buildings 2–9 appts	RA	PJ
	Heat existing houses	RB	PJ
	Heat new buildings 2–9 appts	RC	PJ
	Heat new houses	RD	PJ
	Appliances	R1	PJ
	Lighting	RL	PJ
Transport	Public transports: bus	TA	tkmv/d
	Public transports: tramway	TB	tkmv/d
	Public transports: train	TC	tkmv/d
	Public transports misc.	TD	tkmv/d
	Automobile	TE	tkmv/d
	Truck	TH	tkmv/d
	Delivery vehicles	TL	tkmv/d
Industry	Food, textile, wood, paper, edition	RNH	PJ
	Chemistry, rubber, glass, metal	RCI	PJ
	Machine manufacturing, equipments	RMA	PJ
	Construction	RCO	PJ
	Tertiary	RTR	PJ
	Other	RAL	PJ

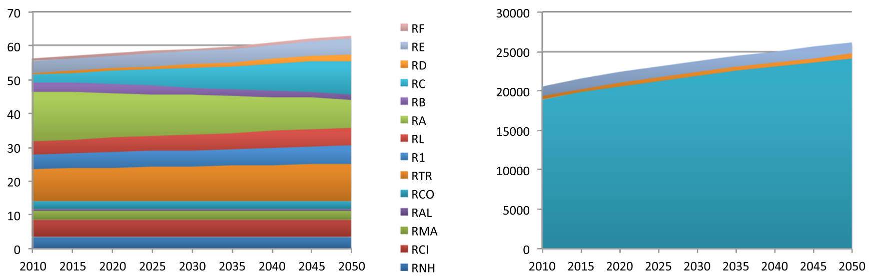

Fig. 3 Evolution of useful demands in PJ (left) and in tkmv/d (right)

Technology portfolio The set of technologies competing for energy conversion and useful demands is described and used in Babonneau et al. (2016, 2017) and ORDECSYS (2013, 2014). Table 2 summarized the available technologies for the key sectors. The present version includes more than 100 technologies.

5.2 Scenario definition

The Swiss energy strategy scenario: The Swiss Federal Office of Energy (SFOE) has proposed a scenario for energy transition, called *Neue Energiepolitik* (NEP). It describes the Swiss Energy Strategy at horizon 2050 ('mittleres' Szenario A-00-2010), We use similar boundary assumptions to those in NEP for the three scenarios developed with ETEM-SG for "Léman

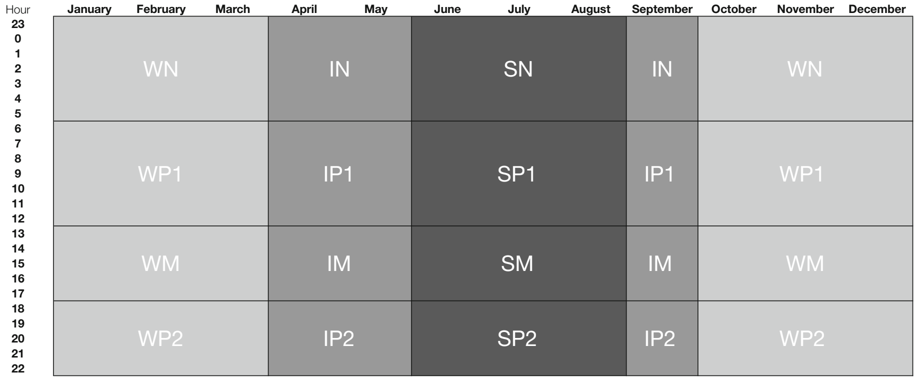

Fig. 4 Definition of timeslices

Table 2 Example of available technologies

Sector	Technology
Electricity generation	Hydro power plant, windmill, PV, gas turbine, cogeneration (heat and electricity), geothermal plant, gas combined power plant, oil-fired steam-cycle, gas CC, gas fuel cell, biomasse plant, etc.
Private transport	EV, PHEV, hybrid, gasoline, diesel, hydrogen, methanol, compressed natural gas, etc.
Residential heating	Electric heat pump, heat plant, district heating, oil furnace, gas furnace, Biogas furnace, wood stove, electric baseboard heater, insulation, etc.

Arc” area. These scenarios will illustrate the importance of taking into consideration power flow constraints at a regional scale. In particular, in the NEP scenario, the emissions of greenhouse gases are caped at a level of 1.5 tons of CO_2-eq per person in 2050. Since the population is expected to attain 1.37 M people in the Arc Lémanique region by 2050 (‘mittleres’ Szenario A-00-2010), we impose as a constraint that the total 2050 emissions should not exceed 2.1 Mt CO_2-eq in the region.

Simulating network congestion: In order to evaluate the impact of power flow constraints and in particular of network congestion on simulation results, three different network settings are compared.

- In the first scenario, it is assumed that the full existing line capacities (i.e., 490 MW) is available for transmission in the region. Without considering inter-regional power transit, the proposed network is oversized and thus congestion does not occur.
- In the second scenario, one assumes that 90% of line capacities is used by power flow transits related to the rest of Swiss and European transmission grid. The residual capacities dedicated for regional activities is decreased by a factor 10 (i.e., 49 MW). The deterministic version of ETEM-SG is solved with these reduced line capacities.
- In the third scenario, one take into account power flow transits using robust optimization techniques as described in Sect. 4. One assumes a nominal saturation rate $\bar{\beta}_l = 0.5$ and variability $\hat{\beta}_l = 0.5$. This corresponds to a nominal capacity $\bar{c}_l = 0.5 c_l$. Here the problem dimension increases in a controlled way as reported in Table 3. As a result, the impact on computational times is limited to 5% increase.

Table 3 Problem dimensions for deterministic and robust formulations

Version	Scenario	# Constraints	# Variables
Deterministic	Scenarios 1 and 2	2’390 k	330 k
Robust	Scenario 3	2’440 k	376 k
Increase		2%	1.4%

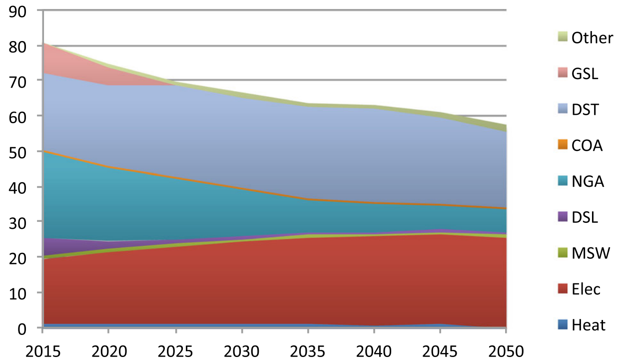

Fig. 5 Energy mix (in PJ/year)

5.3 Simulation results

The results of the simulations, performed for a 2015–2050 horizon planning, are detailed below. The global evolutions of the energy system that is common to the three scenarios is first presented. Then the nodal power balance and prices are compared for the three scenarios in period 2050.

5.3.1 Global energy system evolution

In the electricity sector, Fig. 6 shows that wind mills technology is the main carbon free option to satisfy electricity consumption increase as well as environmental constraints.

At global level, it can be observed that all scenarios lead to very similar situations. It seems that power flow constraints don’t affect investments globally but have instead a significant impact at the nodal spatial scale, as shown in the next subsections. This result is corroborated by the cost of robustness which is very low. The impact of robust optimization on the systemic cost (investment and operations) is limited to 0.5% compared to the cost associated to the deterministic problem in scenario 1. Indeed investments are very similar among the three scenarios but their localization which does not affect the cost.

Figures 5 and 6 display the evolutions, observed for all three scenarios, of regional energy mix and electricity production, respectively. On Fig. 5, one notices an increase of electricity consumption, a reduction of gas use and a gasoline removal. Indeed, to meet the emissions constraint the model replaces gas heaters by heat pumps in residential and building sectors and invest in hybrid and electric vehicles.

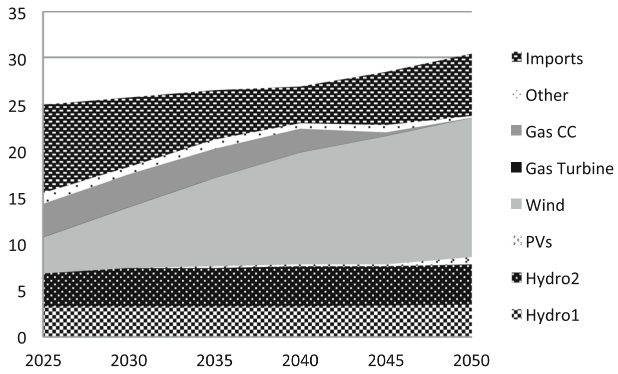

Fig. 6 Electricity production mix (in PJ/year)

5.3.2 Impact of transmission constraints on the 2050 electricity sector

In this subsection one details the simulation results at each node and in particular one observes the impact of power transmission constraints on nodal electricity balance and nodal pricing.
Nodal electricity balance in 2050: Figure 7 shows (in PetaJoules) for the three scenarios (1) total electricity production and consumption at nodes, (2) annual electricity exchanges for local consumption on transmission lines and (3) total 2050 electricity imports at the three import nodes.

It can be observed that power flow constraints can have a significant impact on nodal electricity consumption and production patterns. For example, one observes for Verboix a change from 2.10 PJ in Scenario 1 to 6.12 PJ in Scenario 3 for electricity generation and from 5.86 to 10.35 PJ for total electricity consumption. These different production and consumption patterns are explained by different technological choices at nodes. As expected power flow constraints affect strategic and operational decisions on the full energy system and not only on the electricity sector.

However, in practice the transmission grid is not fixed over time and new investments are usually performed to follow consumption and production evolution. Modeling of investment options on transmission lines would make it possible to increase line capacities and, as a consequence, would limit the changes in power consumption and production patterns.
Nodal electricity prices and congestion in 2050: Figure 8 summarises nodal electricity prices computed by ETEM-SG in 2050 in the three scenarios. It gives the minimum and maximum computed prices over the different timeslices. Figure 8 also displays the maximum utilisation rates of transmission lines over the different timeslices. In scenario 2, utilisation rates include inter-regional transits while in the robust scenario figures correspond to nominal utilisation rates without inter-regional transits.

First and as expected, in the first scenario with large transmission line capacities and without consideration of inter-regional power transit through the transmission grid, the network is oversized and nodal electricity prices are not affected by network congestion. In other words electricity prices are identical at all nodes and vary only in time. In the congested scenarios (scenarios 2 and 3), ETEM-SG generates very different nodal electricity prices. The highest prices are usually computed for central nodes that have no direct connection to imports.

Surprisingly, the minimum electricity price in Verbois, that is connected to imports, is higher in the congested scenarios and higher than the import price. Indeed, this is the impact of power flow constraints. A marginal change in consumption in Verbois would modify the

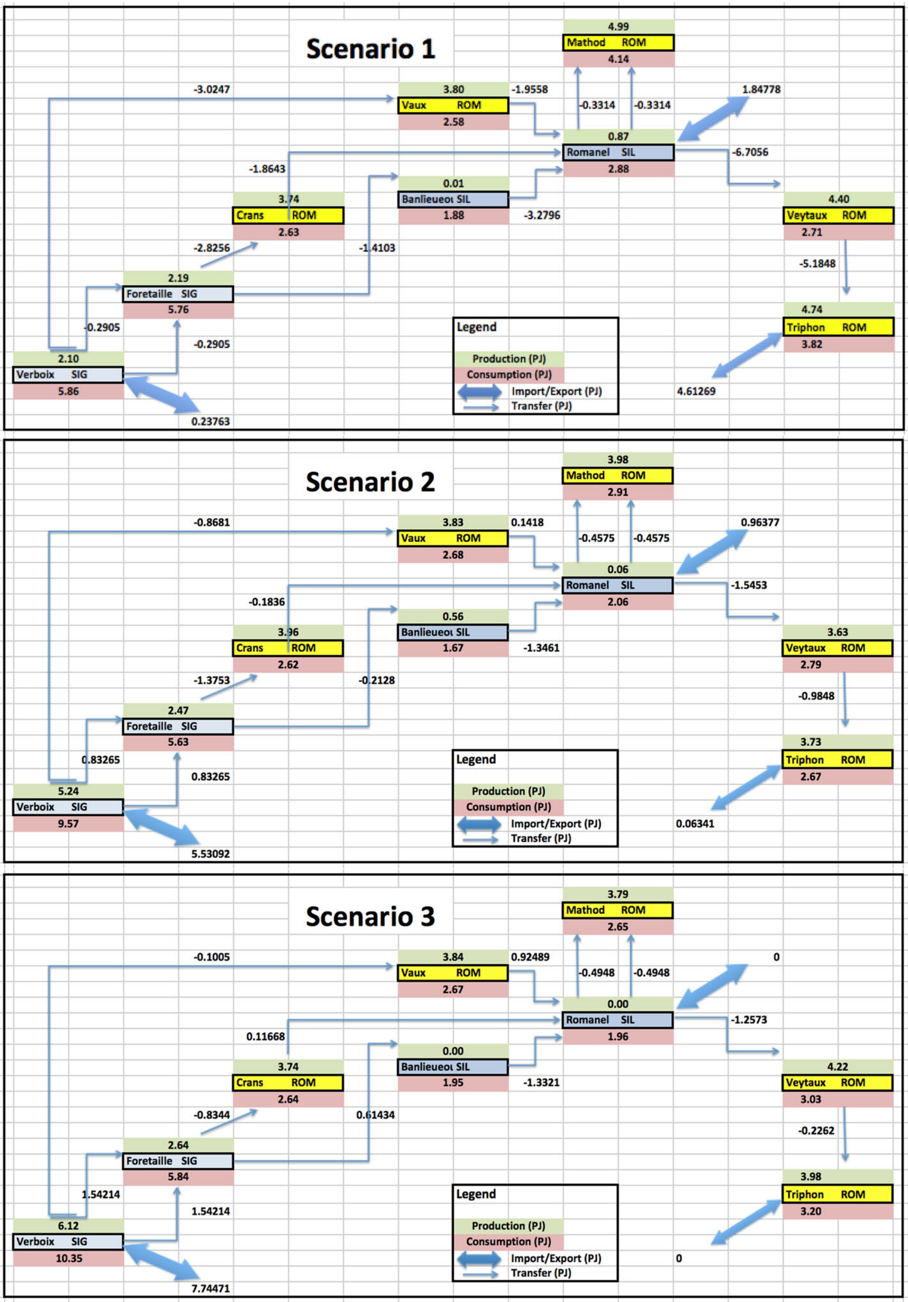

Fig. 7 Nodal electricity balance in 2050

entire system and thus yields to an additional cost difficult to anticipate without a model like ETEM-SG.

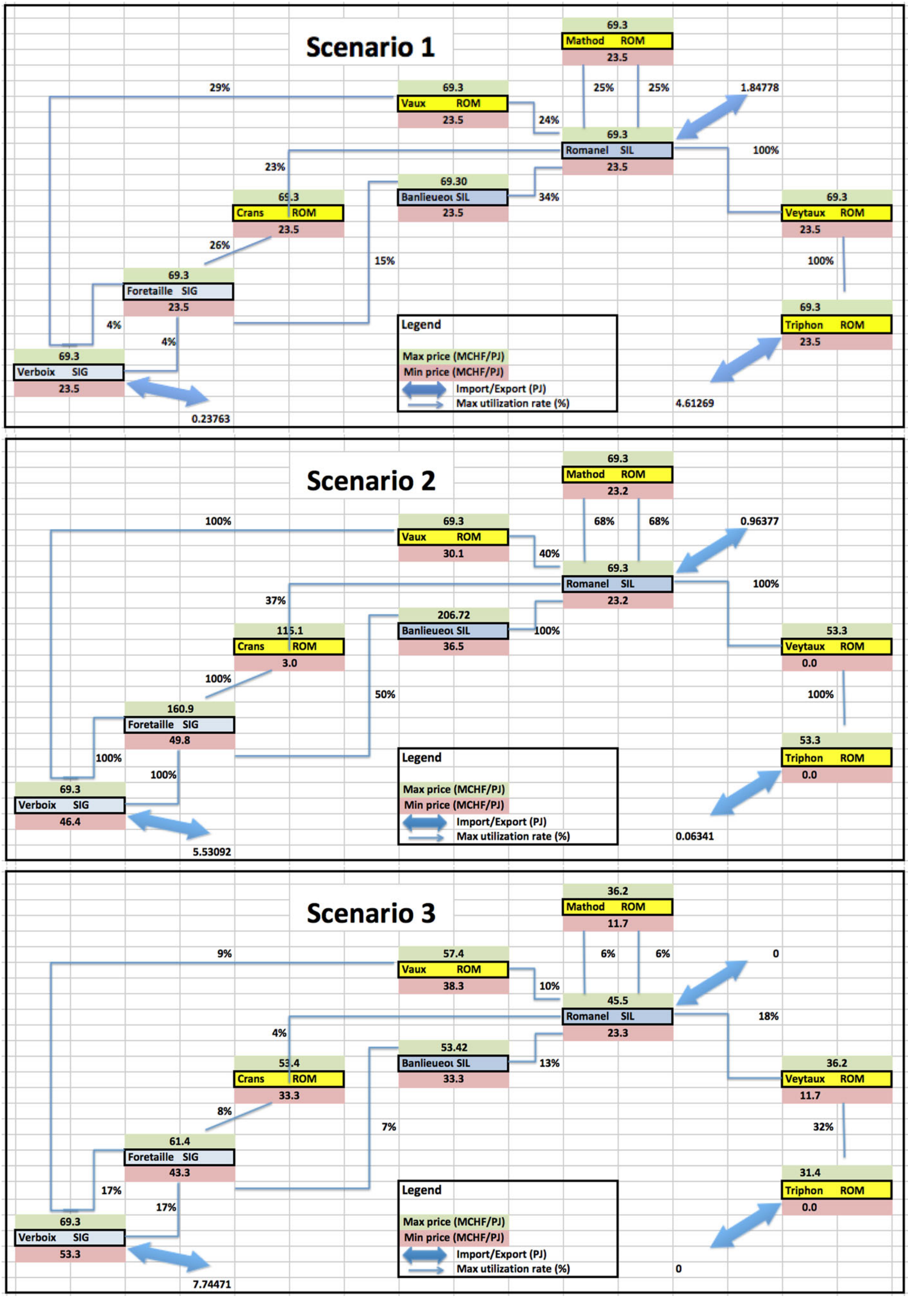

Fig. 8 Statistics on nodal electricity prices (in MCHF/PJ) and on line utilization rate (in %) in 2050

Figure 8 also demonstrates a positive impact of robustness on nodal prices with maximum electricity prices in scenario 3 that are always lower than the ones computed in the two other scenarios. These results can be explained by the fact that robust optimization is a minmax approach and thus provides solutions that are robust for worst case situations, i.e., congested network situations. Note that in this first tentative of applying robust optimization in that context, it was not assumed any known information on inter-regional power flow transit. With such information, one could deliver even more realistic and robust energy analysis.

6 Conclusion

In this paper, the multi-sectoral multi-energy long-term investment planning tool ETEM-SG has been extended to the consideration of power flow constraints in regional transmission grid by implementing a linearized DC power flow model that represents the transmission grid with the main constraints on the power flowing through the different arcs of the electricity transmission network. Then as power flows circulating in a regional transmission grid depend partly on what happens on the transmission grid for a much larger perimeter which is difficult to quantify precisely, robust optimization technique is used to take into account the uncertainty on the capacity limits resulting from inter-regional transit.

The paper shows on a simple case study, that corresponds roughly to the "Léman Arc" region, the relevance of such a modeling exercise for long-term simulations of regional energy systems. First one can notice that power flow constraints together with line capacities have a significant impact on nodal electricity consumption and production patterns and thus on technological choices. Then one can observe a significant effect on maximum nodal prices when considering transit uncertainty using robust optimization.

Future work is envisioned to allow the model ETEM-SG to provide more realistic energy analysis to support decision making. First one should couple the regional ETEM-SG model with a national one (e.g., Weigt and Schlecht 2014) in order to calibrate inter-regional power flow transit properly on simulation results performed with this much larger model. This coupling exercise is not straightforward as it requires an harmonisation of both models in term of assumptions and technological evolutions. For example, regional and national models must provide compatible results in term of electric vehicle penetration as it has a significant impact on electricity grids. A second work will consist in extending the new transmission grid module in ETEM-SG to network improvement decisions. This way ETEM-SG will then be able to make investment trade-off between grid capacity expansions and localized generation technologies.

Acknowledgements This research is supported by the Qatar National Research Fund under Grant Agreement n^{o} NPRP10-0212-170447 and by Canadian IVADO programme (VORTEX Project).

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