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ETEM-SG: Optimizing Regional Smart Energy System with Power Distribution Constraints and Options

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Abstract This paper gives a detailed description of the ETEM-SG model, which provides a simulation of the long-term development of a regional multi-energy system in a smart city environment. The originality of the modeling comes from a representation of the power distribution constraints associated with intermittent and volatile renewable energy sources connected at the transmission network like, e.g., wind farms, or the distribution networks like, e.g., roof top PV panels). The model takes into account the options to optimize the power system provided by grid-friendly flexible loads and distributed energy resources, including variable speed drive powered CHP micro-generators, heat pumps, and electric vehicles. One deals with uncertainties in some parameters by implementing robust optimization techniques. A case study, based on the modeling of the energy system of the "Arc Lémanique" region, shows on simulation results, the importance of introducing a representation of power distribution constraints, and options in a regional energy model.

1 Introduction

This paper deals with the representation of power distribution constraints and options in a regional multi-energy systems analytic model akin to the MARKAL-TIMES family of models. The motivation for these developments is the modeling of the integration of energy systems in smart cities relying in particular on the co-optimization of the cyber and physical layers of the distribution power system (DPS). Increasing penetration of intermittent and volatile renewable energy sources connected at the transmission (e.g., wind farms) or the distribution networks (e.g., roof top PV panels) will impose new operational constraints. On the option side, the advent of grid-friendly flexible loads (FL) and distributed energy resources (DERs) including variable speed drive powered CHP micro-generators, heat pumps, and electric vehicles, provide opportunities to optimize power systems and improve operational and investment efficiencies. Indeed, DERs may have a profound impact on the resilience of network infrastructures.

We propose a modeling framework called ETEM-SG[1], which is a "robust optimization"-based capacity expansion model for an ensemble of energy related infrastructures that

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[1]This acronym stands for *Energy-Technology-Environment-Model with Smart Grids*.

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will be operated in a coordinated way in order to satisfy the demand for services in the urban community, with an optimal use of resources and reduced greenhouse gas (GHG) emissions. The model structure is inspired from MARKAL [9, 10] and TIMES [12]. This long-term expansion model is complemented by a model of electricity distribution, which reveals the future implicit prices on electricity markets under the conditions of massive penetration of renewables, grid storage and demand response. A representation of smart grids has already been introduced in the open-source energy modeling kit OSeMOSYS [11, 16], but our approach is different as one introduces a set of constraints and cost coefficients permitting a modeling of the power distribution in a smart grid environment. A detailed description of the modeling of a power distribution system, with smart grid operations, is given in [3]. In the present paper, this modeling approach is integrated into the ETEM-SG energy model.

The service sectors considered include residential; commercial (HVAC, lighting, computing, electric appliances etc.); industry (process heat, machinery operation); transportation (mass transit, private vehicles, public transportation); water supply and treatment; telecommunications and health. The infrastructure that will be considered encompass primary energy production and transformation of all relevant technologies, and networks such as water, gas, and electricity transmission and distribution (with emphasis on their interaction with renewable energy and other distributed resources). Appliances and energy use technologies will also be considered as part of a broadly construed energy infrastructure and thus include transportation technologies, (e.g., electric, hydrogen fuel cell and other zero-emission vehicles), the various end-use technologies used in household appliances, commercial and industry energy uses, the water supply and treatment technologies and, indeed, the distributed communication and control technologies.

ETEM-SG provides a simulation of the evolution of final energy demand and of environmental impact of energy production and use in smart cities, when one takes full advantage of the potential of load shedding, demand response and integration of renewables provided by smart energy systems. In this modeling approach, one assumes market efficiency at all time scales, with price information reflecting the real marginal cost of the various technologies participating in the supply-demand equilibrium for each energy form. The model is multi-energy, with a particular attention devoted to electricity and power system. The model takes into account the ability of *Distributed Energy Resources* (DERs: broadly construed, distributed flexible loads, generation and other resources) to provide reserves, reactive power compensation, and shift their operation over time so as to reduce losses, congestion, wholesale energy costs, and distribution asset (particularly transformer) wear and tear.

The paper is organized as follows. In Section 2, we present ETEM-SG, which is a multi-energy, long-term technology-rich capacity expansion model. In Section 3, we detail the modeling options adopted to represent the optimal exploitation of demand response, grid storage, electric car charging, distributed system reserve, and reactive power compensation, under a massive penetration of renewables. In Section 4, we present a case study based on the Swiss region of "Arc Lémanique" and we show the impact of including the modeling of power distribution constraints and options on the simulations of optimal development paths. In Section 5, we conclude.

2 The Model ETEM-SG

In this section, we provide a complete description of the linear programming model ETEM-SG. The presentation is organized in three subsections devoted to the structure of the original open-source[2] model ETEM, the introduction of demand-response activities, and the robustification of uncertain constraints, respectively.

2.1 The Structure of ETEM-SG

ETEM is a linear programming model, which represents the optimal capacity expansion in production technology and the flow of resources in the whole energy system. 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 to 50 years usually divided in periods of 1 to 5 years. In each period, one considers a few typical days (e.g., 6 days corresponding to the three seasons—winter, summer, spring-fall—and two week day types—working weekday, weekend-holiday—). Each of these days is subdivided into groups of hours to obtain finally a set of timeslices that will be used to represent load curves and distribution of demand and resource availability in different seasons and at different time of the day.

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[2]ETEM is available as an open-source code that can be downloaded from the site www.ordecsys.com

The model is written in the modeling language AMPL [8]; we give in Appendix A, in pseudocode notations, a complete description of the model sets, parameters, variables, objectives, and constraints that describe the ETEM shell formulation which is very similar to TIMES/MARKAL. These elements are needed when we describe the ETEM-SG modules later on.

2.2 Representing Demand-Response in ETEM

To model demand response, one must allow the energy demands to adapt to implicit pricing signals. To do that, we first define a subset C_f of the set of commodities, which correspond to demand sector with flexible demands. For these flexible demands, the $frac\_dem$ parameters, which determine the proportions of demand that fall in each time slice, are replaced by decision variables, **VAR_frac_dem**. Since the $frac\_dem$ parameter enters linearly the equations of ETEM, it can be changed into a decision variable while staying in the realm of linear programming. Of course, new constraints have to be introduced to limit the possibility of demand displacement.

Additional constraint 1:　$\forall t \in \Theta, S_i, c \in C_f$

$$\sum_{s \in S_i} \textbf{VAR\_frac\_dem}[t, s, c] = \sum_{s \in S_i} frac\_dem[t, s, c]$$
(1)

where the S_i's are the seasons: S_1 is winter, S_2 summer and S_3 intermediate. These constraints ensure the entirety of the demand is met and forbid cross-seasonal load shifting.

Additional constraint 2:　$\forall t \in \Theta, s \in S, c \in C_f$

$$\left(1 - frac\_dem\_dev[t, s, c]\right)$$
$$frac\_dem[t, s, c] \leq \textbf{VAR\_frac\_dem}[t, s, c]$$
$$\leq \left(1 + frac\_dem\_dev[t, s, c]\right) frac\_dem[t, s, c] \quad (2)$$

where the $frac\_dem\_dev[t, s, c]$ parameter is the maximum allowed deviation from the nominal value of the fraction of demand, denoted by $frac\_dem[t, s, c]$. This

parameter can depend on t since the share of the demand that can be shifted may evolve due to the progressive penetration of smart technologies.

2.3 Robustification to Deal with Uncertain Parameters

ETEM-SG implements robust optimization methods to deal with uncertainty. We describe here the robustification technique used for two possible sources of uncertainty on (i) availability factors and (ii) new technology investment costs, respectively. We refer the reader to [1] for more details on robust optimization applied to ETEM constraints.

Robust optimization [6, 15] is an approach that essentially ensures that uncertain constraints in an optimization problem remain feasible for a whole set of possible realizations of random parameters. But, contrary to classical stochastic methods, robust optimization defines the set of possible realizations in an explicit way, e.g., as a polyhedron, rather than implicitly by means of a condition on a probability. This set of relevant realizations is called the uncertainty set. The salient feature of robust optimization is that it reformulates the uncertain constraint into plain inequalities, named the equivalent robust counterpart, that can be efficiently handled through convex optimization methods, and, in particular, linear programming. Application of robust optimization to energy and environment models is described in [4] and [5].

Let us first consider robust constraints for uncertain availability factors. A new parameter avail_factor_var[t, s, p] represents the variability for availability factor of technology p at period t and timeslice s. The set P_rob contains technologies with uncertain availabilities. The approach consists in (i) adding a new constraint on total capacity utilization for a set of uncertain technologies and (ii) applying robust optimization techniques on this uncertain constraints. To robustify the model, one thus introduces the two following sets of constraints:

1. Total capacity utilization equation for uncertain technologies: $\forall t \in \Theta, s \in S, l \in L$

$$\sum_{p \in \text{P\_MAP}[l] \cap \text{P\_rob}, \, c \in \text{C\_ITEMS}[\text{flow\_act}[p]]} \textbf{COM}[t, s, l, p, c]$$

$$<= \sum_{p \in \text{P\_MAP}[l]: p \in \text{P\_rob}} (\text{avail\_factor}[t, s, p] \times \text{cap\_act}[p] \times \text{fraction}[s]$$

$$\times \left(\sum_{k \in 0..t: \, \text{life}[p] \geq k+1, \& t-k \geq \text{avail}[p]} \textbf{ICAP}[t - k, l, p] + \text{fixed\_cap}[t, l, p]) \right)$$

$$- (k_1[t, s, l] \times \textbf{V}[t, s, l] + \sum_{p \in \text{P\_MAP}[l] \cap \text{P\_rob}} \textbf{U}[t, s, l, p]),$$

where **U** and **V** are the dual variables associated to the linear equations that define the uncertainty set. These variables have to satisfy the constraints below (see [4] for details).

2. Additional robust constraints: $\forall t \in \Theta, s \in S, l \in L, p \in \text{P\_MAP}[l] \cap \text{P\_rob}$

$$\mathbf{V}[t, s, l] + \mathbf{U}[t, s, l, p] \geq \text{avail\_factor\_var}[t, s, p] \times \text{avail\_factor}[t, s, p] \times \text{cap\_act}[p]$$

$$\times \text{fraction}[s] \times \left(\sum_{k \in 0..t: \text{ life}[p] \geq k+1, \& t-k \geq \text{avail}[p]} \mathbf{ICAP}[t - k, l, p] + \text{fixed\_cap}[t, l, p] \right).$$

Let cost_icap_var$[t, p]$ denote the variability factor of uncertain investment costs for technologies $p \in \text{P\_rob2}$. The robustification of the model leads to slightly modification of the objective cost function as

$$\mathbf{COST} \geq \ldots \text{ same as above (see objective (27))} \ldots$$
$$+ (1 + \text{disc\_rate})^{\text{nb\_years}[t]}$$
$$\times \sum_{t \in T} (k_2[t] CC \times \mathbf{V_2}[t])$$
$$+ \sum_{p \in \text{P\_rob2}} \mathbf{U_2}[t, p])$$

where $\mathbf{U_2}$ and $\mathbf{V_2}$ are additional variables similar to **U** and **V**. As for uncertain availability factors, additional robustification constraints are added to the ETEM model, $\forall t \in \Theta, p \in \text{P\_rob2}$

$$\mathbf{V_2}[t] + \mathbf{U_2}[t, p] \geq \sum_{l \in L: \ p \in \text{P\_MAP}[l]} \text{cost\_icap}[t, p] \times \text{cost\_icap\_var}[t, p]$$
$$\times \mathbf{ICAP}[t, l, p] / (1 + \text{disc\_rate})^{\text{nb\_years}[t]}.$$

3 Modeling Distribution Options and Constraints

In this section, we focus on representation of the power distribution systems and the exploitation of flexible loads and DERs.

3.1 Network Description and Assumptions

Distribution activities and contraints in ETEM represent the management of centralized and distributed loads, storage and generation units for a local/regional power system at all periods and timeslices. Figure 1 summarizes the simplified topology of a distribution system.

The ∞-bus (b_∞) corresponds to the substation and each downstream bus (b_1 and b_2) corresponds to loads and DERs connected to a distribution feeder. The model's logic is as follows: Conventional generators and wind generators proposed by ETEM are located to bus ∞ and each distribution

feeders corresponds to an ETEM region that is connected to bus ∞. Each feeder bus hosts (i) demand corresponding to conventional loads (typically lighting), which consumes as a by-product "reactive power" whose magnitude depends on a constant power factor, (ii) flexible loads (typically EV battery charging, variable speed drive heat pumps for space conditioning), and (iii) PV generation. EV battery chargers and PV inverters can provide reactive power compensation as needed when they have excess capacity, i.e., when the sun does not shine or when the EV battery is not charging. During a given time slice, flexible loads produce value (or utility to their owners) by providing a service, such as space conditioning that maintains inside temperature within a comfort temperature zone, increasing the state of Charge of thee EV battery and the like.

Although other types of reserves are already modeled, e.g., in the peak reserve equations of ETEM, we focus now on secondary reserves made necessary by renewable generation and uncertainty in conventional loads and generation. The secondary reserve required by the system operator can be provided by conventional centralized generators but also by the flexible loads, in particular by the PHEV/EVs.
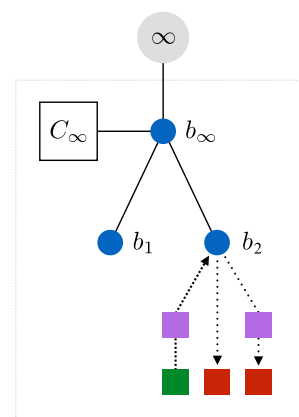
Fig. 1 Representation of the power network. *Circles* denote buses. *Squares* represent power electronics, flexible loads, and distributed generators

Table 1 Useful demands classification (PJ means PetaJoule and tkmv/d means thousand km 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

The model computes real power, reactive power, and reserves associated with each region so as to satisfy load flow, voltage, energy balance, and reserve requirement constraints.

Assumption 1 The transmission network is made up of a single bus, i.e., transmission lines connecting centralized generators G_k, $k \in \{1, \ldots, K\}$, to the bus that supplies all distribution substations have negligible resistance.

Assumption 2 Each distribution feeder is represented by a single aggregated line and a single transformer with all of the demand and distributed resources and generation at the end of the line. The aggregated line has resistance and reactance parameters.

Assumption 3 Demand for energy services and ability for distributed generation or resource provision is specified as follows:

(i) For conventional demand at feeders, such as lights or non-storage/thermal demand, reactive power to be compensated is a given fraction γ^{react} of produced real power.

(ii) For *flexible/storage like loads*, such as thermal storage buildings, space heating/conditioning, electric
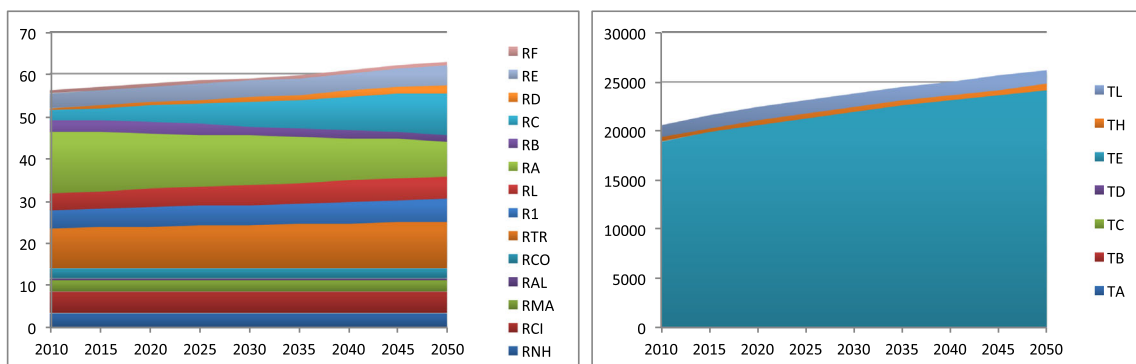
Fig. 2 Evolution of useful demands in PJ (*left*) and in tkmv/d (*right*)

vehicles and the like, it is specified for the whole day. Contraints represents then the dynamics of state and and consumption.

(iii) For distributed resources that accompany electric vehicles or PV generation, inverters, and converters that are embodied can produce reactive power using excess capacity that they may have.

Assumption 4 Generator ramp constraints are negligible.

3.2 Equations to Describe Power Distribution

We give below, in pseudocode notations, a complete description of the model sets, parameters, variables, and constraints.

Sets

$\Theta_d \subset \Theta$: set of periods for which distribution constraints are activated

$P_{con} \subset P$: set of conventional load technologies

$P_{flex} \subset P$: set of flexible load technologies

$P_{genC} \subset P$: set of centralized generation technologies

$P_{genW} \subset P_{genC}$: set of wind generation technologies

$P_{genD} \subset P$: set of decentralized generation technologies

$P_{genPV} \subset P_{genD}$: set of PV generation technologies.

Parameters

$resistance[l]$: resistance (normalized to unity nominal voltage) of distribution feeder line $l \in L$.

$reactance[l]$: reactance (normalized to unity nominal voltage) of distribution feeder line $l \in L$.

res: secondary system reserve factor.

res^w: system reserve factor for wind generation.

γ^{react}: Factor representing reactive power as a proportion of active power consumed by conventional inflexible loads.

$v[l]$: Tension in feeder $l \in L$. The units are chosen so that the tension is normalized with value equal to 1.

$\bar{\theta}[t, s, l], \underline{\theta}[t, s, l]$: Lower and upper bounds on inside temperature of space conditioned facilities

$\theta^{Ambient}[t, s, l]$: Ambient temperature

$\eta^{loss}[t, s], \eta^{gain}[t, s]$: coefficients of heat gain or loss

$\bar{X}(\Theta, S, L)$: Maximum discharge of EV batteries.

Variables

$D^{con}(\Theta, S, L, P_{con})$: Conventional demand load

$D^{flex}(\Theta, S, L, P_{flex})$: Flexible demand load

$D^{ev}(\Theta, S, L)$: EV's demand load

$G^{dec}(\Theta, S, L)$: Decentralized power generation

$G^{\infty}(\Theta, S)$: Centralized power generation

$I(\Theta, S)$: Power imports

$P^{\infty}(\Theta, S)$: Total real power provided by centralized technologies

$P^{\infty}(\Theta, S, L)$: Real power provided by centralized technologies at feeders

$P^{\infty}(\Theta, S, P_{genC})$: Real power provided by centralized technologies

$P(\Theta, S, L)$: Real power load at feeders

$Q^{\infty}(\Theta, S)$: Total reactive power provided by centralized technologies

$Q^{\infty}(\Theta, S, L)$: Reactive power provided by centralized technologies at feeders

$Q^{\infty}(\Theta, S, P_{genC})$: Reactive power provided by centralized technologies

$Q(\Theta, S, L)$: Reactive power load at feeders

$Q^{ev}(\Theta, S, L)$: Reactive power provided by EVs

Fig. 3 Definition of timeslices

$Q^{flex}(\Theta, S, L, P_{flex})$: Reactive power provided by flexible tecnhologies

$Q^{pv}(\Theta, S, L, P_{genPV})$: Reactive power provided by PVs

$R^{\infty}(\Theta, S, L, P_{genC})$: Reserve provided by centralized technologies

$R^{flex}(\Theta, S, L, P_{flex})$: Reserve provided by flexible load

Table 2 Portfolio of electricity-based technologies by category

Category	Label	Code	Comment
Centralized production	Hydro power plant	E01, E02	Existing
	Windmill	E08	Existing
	Gas Turbine	E0E	Existing
	Veytaux (existing turbine)	E00	Existing
	Veytaux (pump)	E0P	Existing
	Tridel Thermal Plant	TIT	Existing
	Tridel Plant (Electricity)	TIE	Existing
	Pierre-de-Plan Plant (heat+electricity)	PDP	Existing
	Lignon Plant (heat)	LIG	Existing
	Chatillon Plant (heat)	CHA	Existing
	Cheneviers Plant (heat and electricity)	ECH	Existing
	Geothermy Plant	ERG	Existing
	Enerbois Plant	ERB	Existing
	Industrial Cogen. Turbine (5 MW)	E6A, E6B	Existing
	Industrial Combined Cycle (5 MW)	E6C	Existing
	Cogeneration	E90, E9G, E9R	Existing
	Gas combined power plant	E0F	New
	Oil-Fired Steam-Cycle	E0D	New
	Gas CC (CHP)	EB1	New
	Oil-Fired Steam-Cycle (CPD)	EB2	New
	Gas fuel cell	EB3	New
Decentralized production	Photovoltaic	E07	Existing
	Existing CHP	RAC	New
	Advanced CHP	RCC	New
Conventional loads	Industry	NHT, CHT MAT,	Existing
		ALT, COT, TRT	Existing
	Appliances	R11	Existing
	Lighting	RCL	Existing
	Electric and solar warm water	RE1, RE2, RE3,	Existing
		RF1, RF2, RF3	Existing
		RFD	Existing
	Electric heaters	RA7, RB7, RC7,	New
		RD7	New
	Geothermal heaters	RCG	New
	Public transport (Train, tramway,	TA2, TB1, TC1	Existing
	bus, miscellaneous, etc)	TD1	Existing
Flexible loads	Electric Heat pump for buildings	RAT	New
	Electric Heat pump for houses	RBT	New
	Electric Heat pump for new buildings	RCT	New
	Electric Heat pump for new houses	RDT	New
	Electric vehicles (EVs)	TES	New

$C^{\infty}(\Theta, S, P_{genC})$: Installed capacity of centralized technologies

$C^{flex}(\Theta, S, P_{flex})$: Installed capacity of flexible technologies

$\theta(\Theta, S, L)$: inside temperature of space conditioned facilities

$X(\Theta, S, L)$: State of discharge of EVs.

3.3 Constraints (from ETEM-SG to Distribution)

This first set of constraints link the ETEM activity and capacity variables with the new variables introduced to describe distribution activities like, conventional and flexible demand loads, centralized and decentralized power generation, electricity imports to grids and installed DER capacities.

Demand load for conventional technology $p \in P_{con}$ at period $t \in \Theta_d$, $s \in S$ and feeder $l \in L$.

$$\mathbf{D^{con}}[t, s, l, p] = \mathbf{COM}[t, s, l, p, \text{"}ELC\text{"}]/\text{cap\_act}[p]/\text{fraction}[s]. \quad (3)$$

Demand load for flexible technology $p \in P_{flex}$ at period $t \in \Theta_d$, $s \in S$ and feeder $l \in L$.

$$\mathbf{D^{flex}}[t, s, l, p] = \mathbf{COM}[t, s, l, p, \text{"}ELC\text{"}]/\text{cap\_act}[p]/\text{fraction}[s]. \quad (4)$$

Demand load for EVs at period $t \in \Theta_d$, timeslice $s \in S$ and feeder $l \in L$.

$$\mathbf{D^{ev}}[t, s, l] = \mathbf{COM}[t, s, l, \text{"}EV\text{"}, \text{"}ELC\text{"}]/\text{cap\_act}[p]/\text{fraction}[s]. \quad (5)$$

Power generation from decentralized technology $p \in P_{genD}$ at period $t \in \Theta_d$, $s \in S$ and feeder $l \in L$.

$$\mathbf{G^{dec}}[t, s, l, p] = \mathbf{COM}[t, s, l, p, \text{"}ELC\text{"}]/\text{cap\_act}[p]/\text{fraction}[s] \quad (6)$$

Power generation from centralized technology $p \in P_{genC}$ at period $t \in \Theta_d$ and $s \in S$.

$$\mathbf{G^{\infty}}[t, s, p] = \sum_{l \in L} \mathbf{COM}[t, s, l, p, \text{"}ELC\text{"}]/\text{cap\_act}[p]/\text{fraction}[s] \quad (7)$$

Electricity imports at period $t \in \Theta_d$ and timeslice $s \in S$.

$$\mathbf{I}[t, s] = \mathbf{IMP}[t, s, \text{"}ELC\text{"}]/\text{cap\_act}[p]/\text{fraction}[s] \quad (8)$$
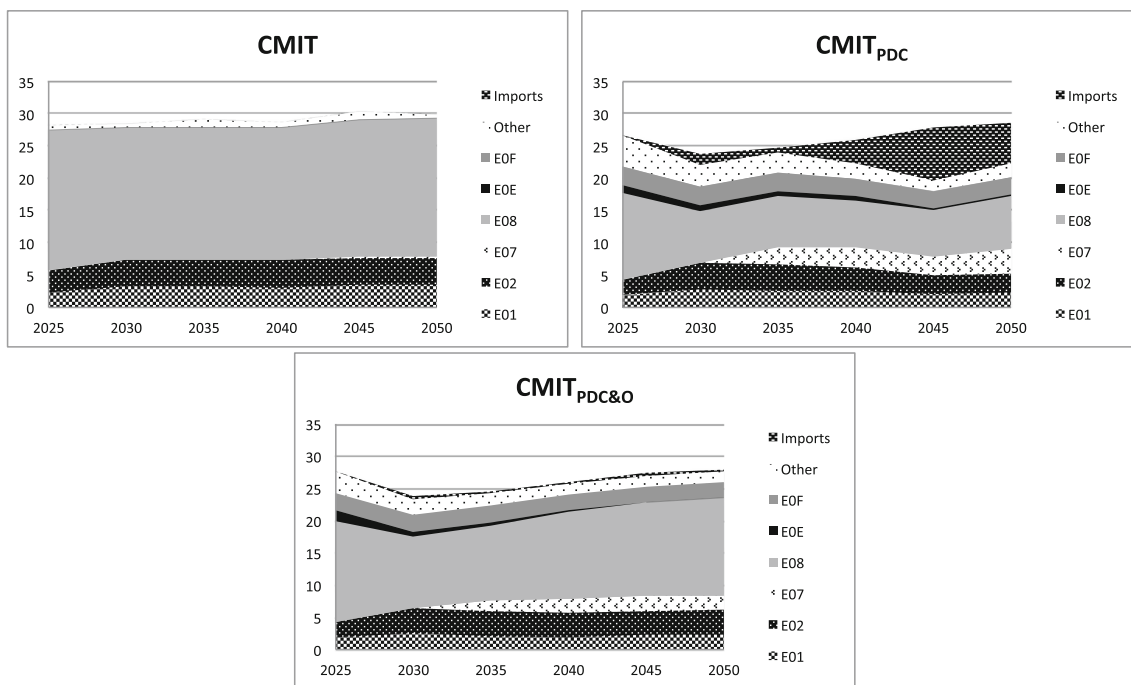

Fig. 4 Evolution of electricity production and use (in PJ/Y)

Installed capacity of centralized technology $p \in P_{genC}$ at $t \in \Theta_d$ and $s \in S$.

$$
\mathbf{C}^\infty[t, s, p] = \text{avail\_factor}[t, s, p] \\
\times \text{cap\_act}[p] \times fraction[s] \\
\times \left(\sum_{\substack{k \in 0...t:\text{life}[p] \geq k+1, \ t-k \geq \text{avail}[p]}} \mathbf{ICAP}[t-k, l, p] \right. \\
\left. + \text{fixed\_cap}[t, l, p] \right) \quad (9)
$$

Installed capacity of flexible technology $p \in P_{flex}$ at $t \in \Theta_d$ and $s \in S$.

$$
\mathbf{C}^\infty[t, s, p] = \text{avail\_factor}[t, s, p] \times \text{cap\_act}[p] \times fraction[s] \\
\times \left(\sum_{\substack{k \in 0...t:\text{life}[p] \geq k+1, \ t-k \geq \text{avail}[p]}} \mathbf{ICAP}[t-k, l, p] \right. \\
\left. + \text{fixed\_cap}[t, l, p] \right) \quad (10)
$$

3.4 Distribution Constraints

These constraints serve to compute real power, reactive power, and reserves associated with each region and times-lice so as to satisfy load flow, voltage, energy balance, and secondary reserve requirement.

Real power load at period $t \in \Theta_d$, $s \in S$ and feeder $l \in L$

$$
\mathbf{P}[t, s, l] = \sum_{p \in P_{con}} \mathbf{D^{con}}[t, s, l, p] \\
+ \sum_{p \in P_{flex}} \mathbf{D^{flex}}[t, s, l, p] + \mathbf{D^{ev}}[t, s, l, p] \\
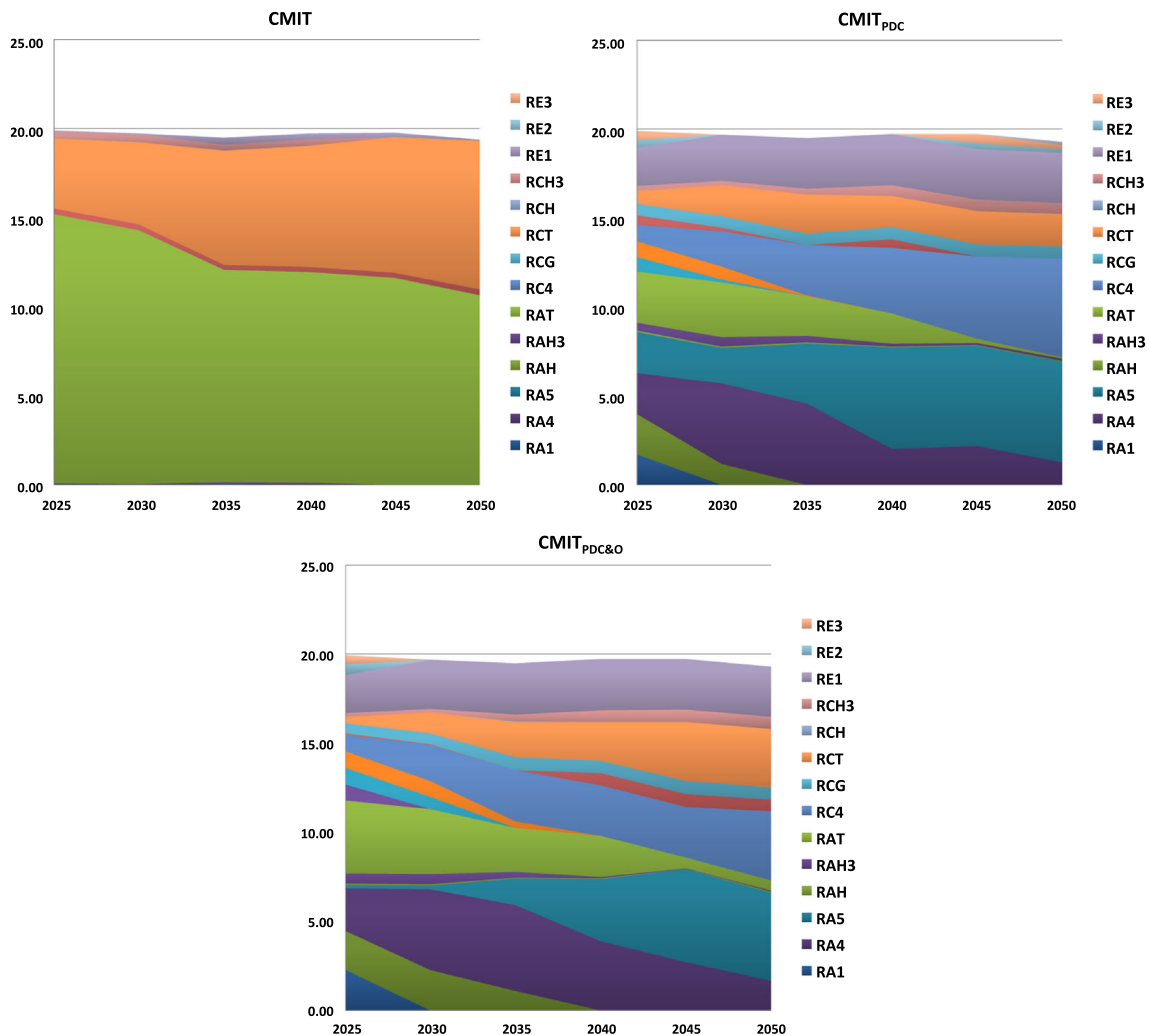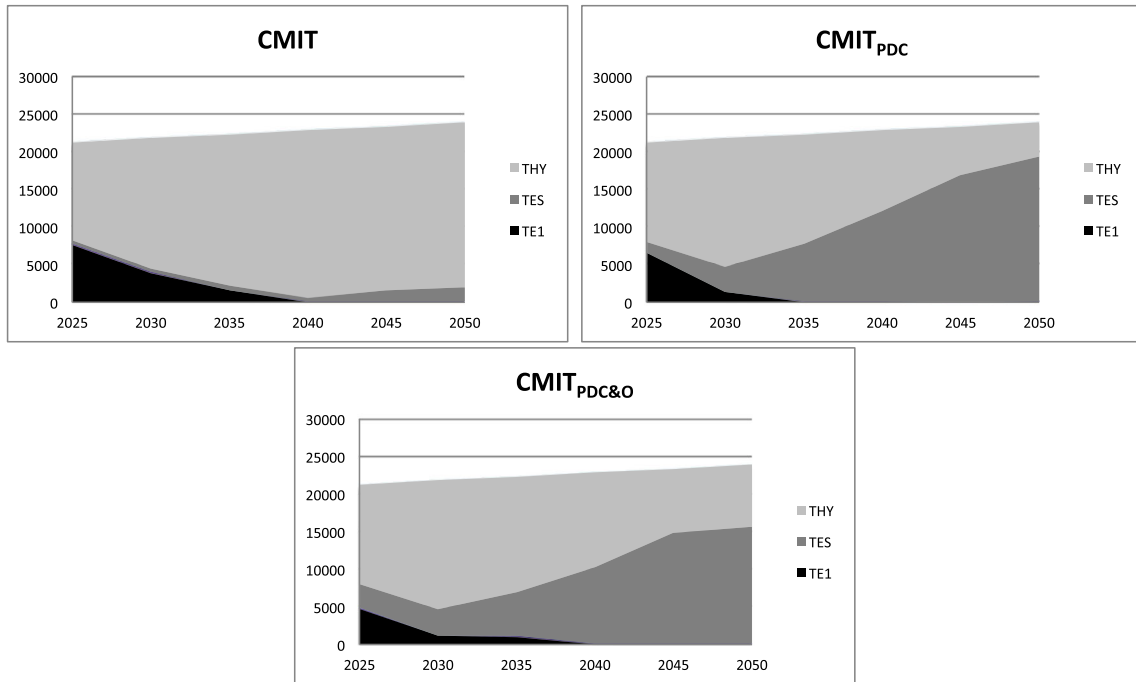- \sum_{p \in P_{genD}} \mathbf{G^{dec}}[t, s, l, p] \quad (11)
$$

Fig. 5 Evolution of heating activities in buildings (in PJ)

Fig. 6 Evolution of transport activities (in tkmv/d)

Reactive power to be compensated at period $t \in \Theta_d, s \in S$ and feeder $l \in L$

$$\mathbf{Q}[t,s,l] = \gamma^{react} \sum_{p \in P_{con}} \mathbf{D^{con}}[t,s,l,p] - \sum_{p \in P_{flex}} \mathbf{Q^{flex}}[t,s,l,p]$$
$$- \mathbf{Q^{ev}}[t,s,l] - \sum_{p \in GenPV} \mathbf{Q^{pv}}[t,s,l,p] \quad (12)$$

Total real power provided by centralized technologies at period $t \in \Theta_d$ and $s \in S$

$$\mathbf{P^{\infty}}[t,s] = \sum_{p \in GenC} \mathbf{G^{\infty}}[t,s,p] + \mathbf{I}[t,s]$$
$$= \sum_{l \in L} \mathbf{P^{\infty}}[t,s,l] \quad (13)$$

Total reactive power provided by centralized technologies at period $t \in \Theta_d$ and $s \in S$

$$\mathbf{Q^{\infty}}[t,s] = \sum_{p \in GenC} \mathbf{Q^{\infty}}[t,s,p] = \sum_{l \in L} \mathbf{Q^{\infty}}[t,s,l] \quad (14)$$

Real power provided by centralized technologies at period $t \in \Theta_d, s \in S$ and feeder $l \in L$

$$\mathbf{P^{\infty}}[t,s,l] = \mathbf{P}[t,s,l] + \frac{resistance[l]}{v[l]^2} \left\{ \mathbf{P}[t,s,l]^2 + \mathbf{Q}[t,s,l]^2 \right\} \quad (15)$$

Reactive power provided by centralized technologies at period $t \in \Theta_d, s \in S$ and feeder $l \in L$

$$\mathbf{Q^{\infty}}[t,s,l] = \mathbf{Q}[t,s,l] + \frac{reactance[l]}{v[l]^2} \left\{ \mathbf{P}[t,s,l]^2 + \mathbf{Q}[t,s,l]^2 \right\} \quad (16)$$

Remark 1 Linearized versions of Eqs. (15–16) are obtained through a Taylor development in the neighborhood of the optimal solution.
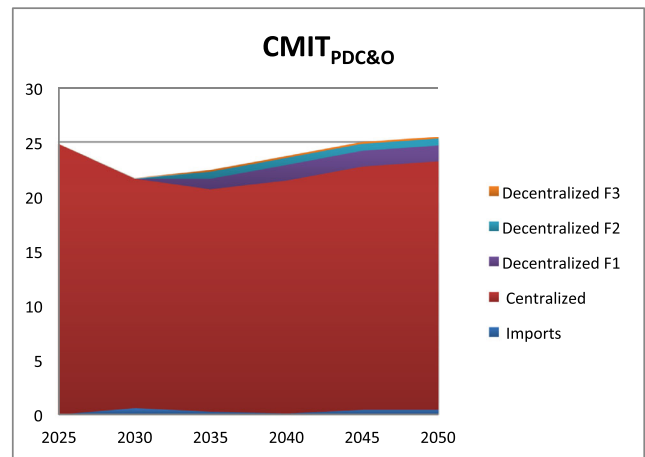
Fig. 7 Real power generation converted energy equivalent (in PJ)

$$\mathbf{P}^{\infty}[t,s,l] = \mathbf{P}[t,s,l] + \frac{resistance[l]}{v[l]^2}\{(P^0[t,s,l])^2 + (Q^0[t,s,l])^2 + 2P^0[t,s,l](\mathbf{P}[t,s,l]$$
$$-P^0[t,s,l]) + 2Q^0[t,s,l](\mathbf{Q}[t,s,l] - Q^0[t,s,l])\} \tag{17}$$

$$\mathbf{Q}^{\infty}[t,s,l] = \mathbf{Q}[t,s,l] + \frac{reactance[l]}{v[l]^2}\{(P^0[t,s,l])^2 + (Q^0[t,s,l])^2 + 2P^0[t,s,l](\mathbf{P}[t,s,l]$$
$$-P^0[t,s,l]) + 2Q^0[t,s,l](\mathbf{Q}[t,s,l] - Q^0[t,s,l])\} \tag{18}$$

An updating scheme has to be implemented when using the linearized version. At each iteration P^0 and Q^0 are replaced by the last computed real and reactive power solutions. In practice, one converges very rapidly to a fixed-point (say 5-10 iterations).

Reserve provided by centralized and flexible loads at $t \in \Theta_d$, $s \in S$ and feeder $l \in L$

$$\sum_{p \in P_{genC}} (1+\alpha)\mathbf{R}^{\infty}[t,s,l,p] + \sum_{p \in P_{flex}} \mathbf{R}^{\mathbf{flex}}[t,s,l,p]$$
$$\geq res \sum_{p \in P_{con}} \mathbf{D}^{\mathbf{con}}[t,s,l,p]$$
$$+ res^w \sum_{p \in P_{genW}} \mathbf{G}^{\infty}[t,s,l,p] \tag{19}$$

Capacity constraints on centralized generation $p \in P_genC$ at $t \in \Theta_d$ and $s \in S$

$$\mathbf{R}^{\infty}[t,s,l,p] \leq \mathbf{P}^{\infty}[t,s,l,p] \leq \mathbf{C}^{\infty}[t,s,l,p] - \mathbf{R}^{\infty}[t,s,l,p] \tag{20}$$

Capacity constraints on flexible loads $p \in P_flex$ at $t \in \Theta_d$ and timeslice $s \in S$

$$\mathbf{R}^{\mathbf{flex}}[t,s,l,p] \leq \mathbf{P}^{\mathbf{flex}}[t,s,l,p] \leq \mathbf{C}^{\mathbf{flex}}[t,s,l,p] - \mathbf{R}^{\mathbf{flex}}[t,s,l,p] \tag{21}$$

Bounds on reactive power compensation provided by flexible loads $p \in P_{flex}$ at $t \in \Theta_d$, $s \in S$ and $l \in L$

$$0 \leq \mathbf{Q}^{\mathbf{flex}}[t,s,l,p] \leq \mathbf{C}^{\mathbf{flex}}[t,s,l,p] - \mathbf{P}^{\mathbf{flex}}[t,s,l,p] \tag{22}$$

State equations-1: Describe the dynamics of indoor temperature and the interval in which the temperature must remain when using to flexible heating technologies at $t \in \Theta_d$, $s \in S$ and $l \in L$

$$\theta[t, SUCC[s], l] = \theta[t,s,l] + \eta^{loss}[t,s](\theta^{Ambient}[t,s,l]$$
$$-\theta[t,s,l]) - \eta^{gain}[t,s]\mathbf{P}^{\mathbf{flex}}[t,s,l,p] \tag{23}$$
$$\underline{\theta}[t,s,l] \leq \theta[t,s,l] \leq \bar{\theta}[t,s,l] \tag{24}$$

State equations-2: Describe the dynamics and the minimum value of the state of discharge of EV's at $t \in \Theta_d$, $s \in S$ and $l \in L$

$$\mathbf{X}[t, SUCC[s], l] = \mathbf{X}[t,s,l] + \text{cap\_act}[p] \times \text{fraction}[s] \times (\mathbf{D}^{\mathbf{ev}}[t,s,l]$$
$$-\mathbf{P}^{\mathbf{flex}}[t,s,l, \text{"EV"}]) \tag{25}$$
$$\mathbf{X}[t,s,l] \leq \bar{X}[t,s,l]. \tag{26}$$

4 Case Study

We apply the model to a case study inspired from the regionl power system of the Arc-Lémanique region in Switzerland (Cantons of Vaud and of Geneva). We consider three distribution feeders corresponding, globally, to the three power distribution companies operating in the region. The energy model for three regions associated with the feeders is adapted from a previous ETEM model that had been developed for the whole region, without consideration of distribution constraints in previous projects.[3]

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[3]We refer to the RITES [14] and TOU [2] projects, which were supported by the Swiss Federal Office of Energy
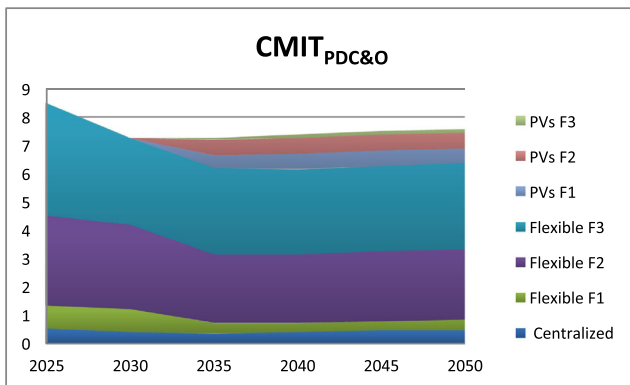
Fig. 8 Reactive power compensation (in PJ/Y)

Remark 2 The objective of the numerical simulations is to illustrate the impact of introducing a representation of distribution constraints and options in a regional energy model, and not to provide a very precise representation of the energy policy choices in this region. Therefore, the technical parameters used in the distribution module are not giving a very accurate description of the three distribution networks. This is the case, in particular, for the choice of a power factor of 0.93, similar to the one observed in US regions, associated with reactive power consumption by conventional loads of 0.35 KVar for each 0.93KW that they consume.

4.1 Linking with the Swiss Energy Strategy Scenario Horizon - 2050

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 [7]. We use similar boundary assumptions to those in NEP for the three scenarios developed with ETEM-SG for the Arc Lémanique region. These scenarios will illustrate the importance of taking into consideration constraints and options at distribution level in the assessment
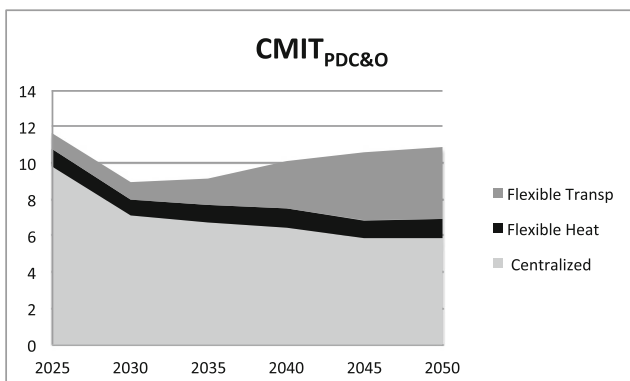
Fig. 9 System reserve converted energy equivalent (in PJ)

of energy/climate policies 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.

In the three scenarios, the penetration of variable renewable energies (VRE), that is PV and wind generation, is not limited. This allows us to evaluate the impact of power distribution constraints and options on the deployment of wind and solar technologies. The three scenarios are:

1. *CMIT* - a Climate MITigation scenario compatible with NEP assumptions on demands and emissions but obtained without distribution considerations in the ETEM model.
2. $CMIT_{PDC}$ - a $CMIT$ scenario with consideration of Power Distribution Constraints (on reserve, reactive power compensation, etc.) but without the options offered by DERs for system services (although PVs can contribute to reactive power compensation).
3. $CMIT_{PDC\&O}$ - a $CMIT$ scenario with consideration of Power Distribution Constraints and Options.

4.2 Energy Consumption in 2010

in 2010, the total annual energy consumption of the Arc Lémanique region was 114.3 PJ[4] and, overall, CO_2 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.

4.3 Useful Demands and Timeslices

Table 1 gives the useful demands considered in the case study and Fig. 2 displays their assumed evolution up to 2050. These demands are then 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. 3.
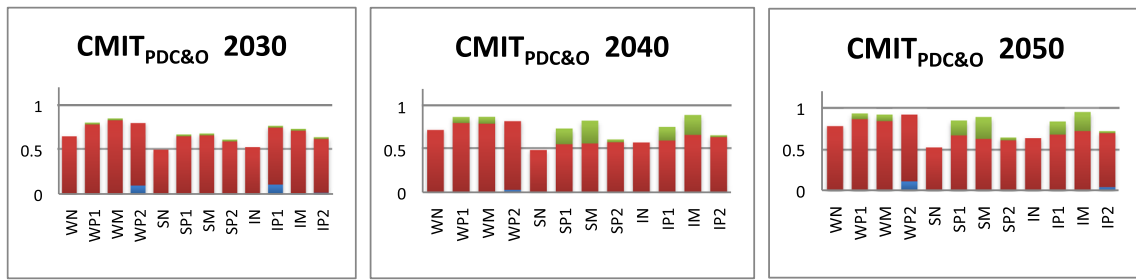
4.4 Portfolio of Technologies

Table 2 gives the list of all electricity production or consumption technologies that appear in the model.

4.5 Analysis and Comparison of the Scenarios

To compare the simulations results for the three scenarios ($CMIT$, $CMIT_{PDC}$ and $CMIT_{PDC\&O}$) , we concentrate

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[4]31.7 TWh.

Fig. 10 Real power generation (in GW). Legend: *Green* for decentralized, *red* for centralized, and *blue* for imports

on the time interval 2025-2050, since it is when the VRE technologies will have the possibility to penetrate strongly the energy system.

Figure 4 shows the evolution of the power supply mix for the three scenarios. The scenario $CMIT$ is the one that would be proposed by a TIMES or ETEM model, when there is no limit for the penetration of VREs and no consideration of secondary reserve requirement associated to VREs nor reactive power compensation. Simulation results show that the stringent emission constraint is satisfied mainly by a strong deployment of wind farms (see E08 in Fig. 4), i.e., 72 % of total electricity generation, and of electric heat pump in the heating sector (see RAT and RCT in Fig. 5). Penetration of EVs is not needed in that situation (see TES in Fig. 6). This scenario is of course not realistic as a power distribution system with 72 % VRE generation would face serious resilience and stability issues. So, in practice, in the use of these existing models one should introduce some arbitrary constraints limiting the proportion of VRE generation to a range of 30 to 40 %.

The scenario $CMIT_{PDC}$ confirms that power distribution constraints have a significant impact on VRE penetration. The share of VREs, i.e. wind farms (E08) and PVs (E07) decreases to 40 % of total electricity generation as shown in Fig. 4. This is consistent with the current practice, alluded to above, which recommends a maximum 30-40 % share for VRE generation (e.g., Since 2008, French government set a legal limit of 30 % on the level of instan-

taneous production of intermittent sources [13]). Compared to scenario $CMIT$ we observe a larger penetration of solar panels due to their property of reactive power compensation. The other production technologies are gas combined-cycle power plants (E0F), gas turbines (E0E), and hydro power plants (E01 and E02). We notice that imports, assumed to be carbon free in this exercise, contribute in the scenario $CMIT_{PDC}$ in satisfying the emissions reduction constraint. An upper bound on electricity import was imposed but was not active. These imports come from France (using mostly nuclear) and other regions of Switzerland (using mostly hydro and nuclear) and are not distinguished in the model. We observe in Figure 6 that, in both scenarios with power distribution constraints ($CMIT_{PDC}$ and $CMIT_{PDC&O}$), EV technology (TES) is much needed to reach the GHG emissions reduction objectives. The other types of car used are hybrid (THY) and diesel (TE1) vehicles. In the residential sector, the situation for heating is very similar in these scenarios with investment in heat pumps technologies (i.e., around 20 % of the heating sector).

Finally, when smart systems are fully exploited, in scenario $CMIT_{PDC&O}$, flexible loads from heat pumps and electric vehicles reach around 21 % of total electricity consumption in 2050. The deployment of these smart grid options acts as positive vector for VREs penetration. The share of VRE generation is now around 61 %, to be compared to the 40 % when smart options are not considered (see Fig. 4). In that context imports are not needed anymore.
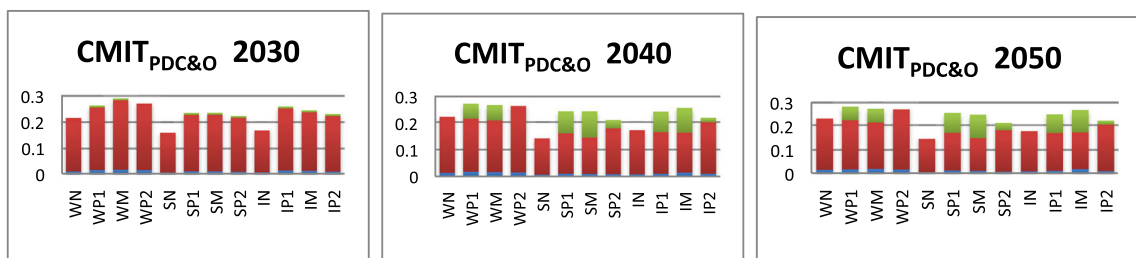
Fig. 11 Load curve for Reactive power Generation (in GW). Legend: *Green* for Pvs, *red* for flexible, and *blue* for centralized

This increase is due to the possible contribution of DREs to providing secondary reserve to cope with intermittency of Wind and solar generation.

4.6 Power Distribution Options for $CMIT_{PDC\&O}$ Scenario

We now focus our analysis on the $CMIT_{PDC\&O}$ scenario only and we present the main impacts of flexible loads, PVs, electric vehicles, etc, on real power generation (Fig. 7), reactive power compensation (Fig. 8) and secondary reserve requirement (Fig. 9). For real and reactive power generation, we display associated load curves in Figs. 10 and 11, respectively.

In Fig. 7, decentralized production corresponds uniquely to solar generation as indicated in Fig. 4. Detailed loads displayed on Fig. 10 show this solar contribution on day timeslices.

One notices on Figs. 8 and 11 that reactive power is first compensated by flexible loads and then by PVs and centralized power plants.

Figure 9 confirms the key role played by EVs and flexible heating technologies for providing system secondary reserve. This shows that EVs and flexible loads will be facilitators for the transition of the energy system toward a low carbon economy.

4.7 Implementing Robust Optimization

4.7.1 Uncertain energy prices

We illustrate here the introduction of robustness in ETEM-SG when energy prices are uncertain. We assume that prices of oil-based energies (gazoline/diesel for transportation and fuel oil for heating) have a 50 % variability while prices of coal, gas and electricity have a lower variability of 20 %. We apply robust optimization as described in Section 2.3 on the smart scenario, i.e., $CMIT_{PDC\&O}$. We first observe that the changes compared to the deterministic results presented in the previous section are not negligible but somehow limited. The reason is that the CMIT scenarios are already very constrained by the emissions limit, so the

Fig. 12 Example of diversification effect of robust optimization on the transportation sector (Source [1])
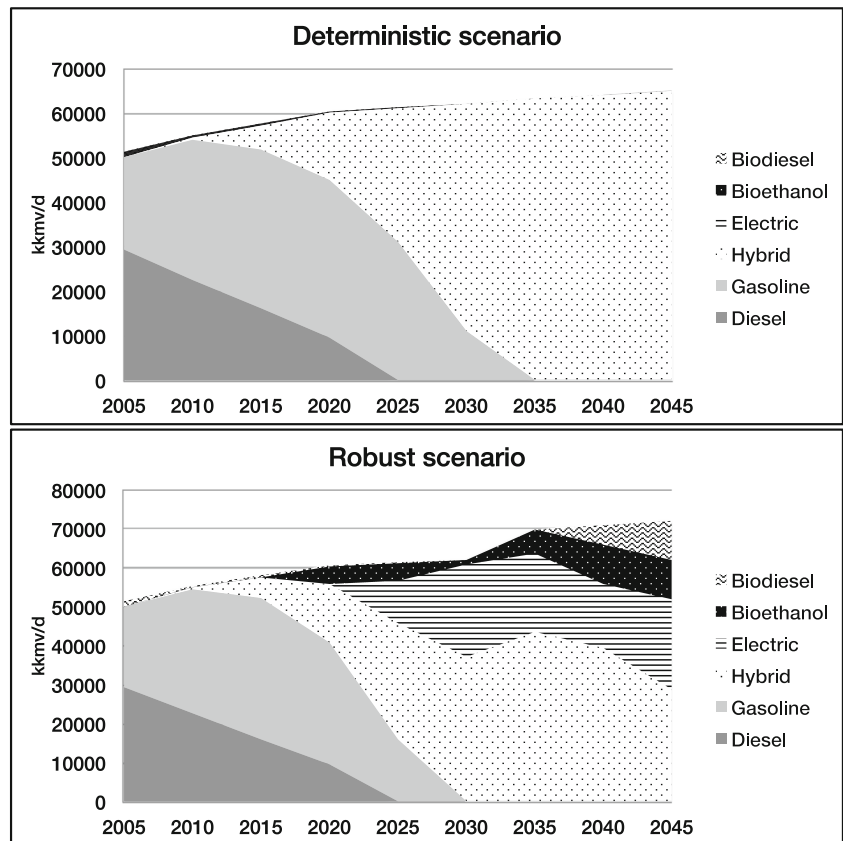
model has no much latitude to adapt the energy system and the technology portfolio to uncertain energy prices. Despite this, we observe an interesting behavior:

- First, as expected, the highest uncertainty being associated with oil-based energies, the main impact of robustness is to be observed on the transportation sector, in particular with a strongest penetration of EVs. In 2050 the share of EVs increases by 20 % compared to the deterministic scenario.

- The second effect concerns the electricity sector whose production is directly impacted by uncertain prices. We notice an increase of electricity consumption of 1 PJ in 2050 combined with a significant growth of wind and solar generation. In 2050, 2 PJ (i.e., 7 % of total production) are additionally produced augmenting the share of VRE generation to around 63 %. The increase of renewable generation is mainly used by EVs.

- A third non-expected consequence is the substitution of 50 % of gas furnaces by oil ones in the appartement heating sector. First, the highest VRE generation gives more room to fossil energies in the satisfaction of the emissions constraint. In that context, the model favours technology diversification to reduce the risk related to uncertainty.

- Finally, and more generally, in this analysis, as well as in the previous studies, one may observe a diversification effect, which reduces the risk related to uncertainty.

4.7.2 Uncertain availability factors

Robust optimization approach can be used to deal with uncertainty concerning the availability of existing and new technologies. This has already been demonstrated in a TIMES model for Europe dealing with energy supply security [4] and in the ETEM-AR model[5] in which the uncertainty concerns the availability of electric cars [1]. We reproduce below the simulation results of [1] on the transportation sector, which show the diversification effect of applying robust optimization (Fig. 12).

Note that a similar effect would be observed for the Arc Lémanique region but it is not discussed in this paper for the sake of brevity.

5 Conclusion

In this paper, we have described a complete regional energy model, ETEM-SG, which contains a new module devoted to the description of power distribution options and

constraints. The model has been tested on a case study corresponding, in big strokes, to the "Léman region" in Switzerland. Computationally, it demonstrates that the approximation of a non-linear power distribution model by a linear one is efficient. The proposed iterative approach converges very rapidly to a fixed-point.

The experiment also shows that ETEM-SG captures the substantial help provided by DERs for a strong penetration of renewables. The interpretation of the three scenarios that have been simulated shows that:

- We first demonstrate that it is essential to handle power distribution constraints in such long-term analysis to produce realistic energy systems that are compatible with network stability requirements. We propose here a global approach that includes reactive power compensation, system secondary requirements, power distribution losses, etc, while classical approaches introduce some arbitrary constraints limiting artificially the proportion of VRE generation.

- The consideration of power distribution options and constraints does bring significative changes in technology choices, in the space heating and transport sectors. In general the electricity consumption and local production are reduced, when power distribution losses and costs are better represented.

- In the context of stringent emissions reduction policies, EVs with their batteries as well as flexible loads play a key role in the penetration of electricity-based technologies and intermittent productions. They facilitate the supply/demand balance for electricity by smoothing production and consumption. They also help significantly to the stability of the power distribution systems with their contribution to reactive power compensation and reserve requirements.

- Including robustification on energy prices in the design of scenarios amplifies the VRE penetration and leads to higher diversification in the technology portfolio. The proposed approach can handle in a same modelling exercise a large set of uncertainty sources (e.g., import prices, technology costs, technology efficiency and availability, etc) without increasing dramatically CPU time.

ETEM-SG can still be extended to include more constraints related to the distribution grid, in particular those related to primary (fast) reserve, that can be provided by battery packs, supercapacitors, or flywheels, etc. ETEM-SG is also currently extended to include power transmission constraints for interconnected regional power systems.

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[5]ETEM Adaptation Robust

Appendix ETEM shell formulation

A.1 Sets, Parameters, and Variables

A.1.1 Sets

They provide a nomenclature of all the elements in the energy model.

Θ : set of periods
S : set of timeslices
C : set of commodities
L : set of regions
P : set of technologies
POL : set of emission types
$P\_PROD[c] \subset P$: set of technologies that are producing commodity $c \in C$
$P\_CONS[c] \subset P$: set of technologies that are consuming commodity $c \in C$
$P\_MAP[l] \subset P$: set of technologies that are installed in region $l \in L$
$C\_MAP[p] \subset C$: set of commodities that are input or output for technology $p \in P$
$C\_ITEMS[flow\_act[p]] \subset C$: set of commodities in the activity flow
C_s : set of storage commodities
$SUCC[s]$: successive timeslice of $s \in S$ used for storage

A.1.2 Parameters

These are values that must be entered by the user. The complete definition of all the parameters constitutes the database of the model.

Economic parameters: they are used to define the objective function.

disc_rate: Annual discount rate
nb_years[t]: Number of years in period $t \in \Theta$
cost_icap[t, p]: Unit cost of capacity increase for technology p at period t
fixom[t, p]: Fixed maintenance cost per unit of installed capacity for technology p at period t
varom[t, p]: Variable cost per unit of activity level for technology p at period t
cost_imp[t, s, c]: Unit cost of import for commodity c in region s at period t
cost_exp[t, s, c]: Unit cost of export for commodity c in region s at period t
cost_deliv[t, s, p, c]: Unit cost of delivery for commodity c in technology p in region s at period t

taxe[t, π]: Unit emission tax for pollutant π at period t
salvage[t, p]: Salvage value (in %) of technology p that has been installed in period t
avail[p]: Date of availability of technology p
life[p]: Life duration of technology p.

Parameters Related to Demands:

network_efficiency[c]: Global efficiency (≤ 1) of distribution network for commodities other than electricity. The losses in the power distribution networks will be considered in the module representing the activities related to power distribution.
frac_dem[t, s, c]: Fraction of (useful) demand for commodity c occurring in timeslice s of period t
demand[t, c]: Useful demand for commodity c in period t.

Parameters Related to Technology Capacities:

avail_factor[t, s, p]: Availability factor
cap_act[p]: Capacity factor (translates power into energy)
fraction[s]: Duration of time slice s in fraction of year
fixed_cap[t, l, p]: Residual capacity.

Parameters Defining Bounds:

act_bnd_lo[t, s, l, p]: Lower bound on activity
act_bnd_up[t, s, l, p]: Upper bound on activity
imp_tot_bnd_lo[t, c]: Lower bound on import
imp_tot_bnd_up[t, c]: Upper bound on import
exp_tot_bnd_lo[t, c]: Lower bound on export
exp_tot_bnd_up[t, c]: Upper bound on export
cap_bnd_lo[t, l, p]: Lower bound on capacity
cap_bnd_up[t, l, p]: Upper bound on capacity
icap_bnd_lo[t, l, p]: Lower bound on investment
icap_bnd_up[t, l, p]: Upper bound on investment.

A.1.3 Variables

The decision variables are the following

$COST$: System cost (value of objective function)
$COM(\Theta, S, L, P, C)$: Activity level; production or consumption of commodity C in region L for process P during timeslice S at period Θ

$ICAP(\Theta, L, P)$: Investment level (increase of capacity) for process P at period Θ and in region L

$EXP(\Theta, S, C)$: Exports of commodity C during timeslice S at period Θ

$IMP(\Theta, S, C)$: Imports of commodity C during timeslice S at period Θ

$EMI(\Theta, POL)$: Emission level of pollutant POL at period Θ resulting from activity levels.

A.2 Objective Function

The objective function is the total discounted system cost minus the salvage value of the residual life of equipments at the end of the planning period.

$$\min \mathbf{COST} \tag{27}$$

with

$$
\begin{aligned}
\mathbf{COST} \geq \sum_{t \in \Theta} (1 + \text{disc\_rate})^{-\text{nb\_years}[t]} \Bigg\{ & \sum_{l \in L, p \in P\_MAP[l]} \text{cost\_icap}[t, p]\mathbf{ICAP}[t, l, p] \\
& + \sum_{l \in L, p \in P\_MAP[l]} \text{fixom}[t, p] \Big(\sum_{\substack{k \in \{0 \dots t\} : \\ \text{life}[p] \geq k+1, \\ t-k \geq \text{avail}[p]}} \mathbf{ICAP}[t, l, p] \\
& \sum_{s \in S} \Big(\sum_{l \in L, p \in P\_MAP[l]} \text{varom}[t, p] \sum_{c \in C\_ITEMS[\text{flow\_act}[p]]} \mathbf{COM}[t, s, l, p, c] \\
& + \sum_{c \in IMP} \text{cost\_imp}[t, s, c]\mathbf{IMP}[t, s, c] - \sum_{c \in EXP} \text{cost\_exp}[t, s, c]\mathbf{EXP}[t, s, c] \\
& + \sum_{\substack{l \in L, p \in P\_MAP[l], \\ c \in C\_MAP[p]}} \text{cost\_deliv}[t, s, p, c]\mathbf{COM}[t, s, l, p, c]) \\
& + \sum_{\pi \in POL} \text{taxe}[t, \pi]\mathbf{EMI}[t, \pi] \\
& - \sum_{\substack{l \in L, p \in P_M AP[l] : \\ t \geq \text{avail}[p] \ \& \ (t + \text{life}[p]) \geq T+1}} \text{salvage}[t, p] \times \text{cost\_icap}[t, p]\mathbf{ICAP}[t, l, p] \Bigg\}
\end{aligned}
$$

A.3 Constraints

A.3.1 Commodity Balance Equations

For each commodity, or energy form other than electricity, what is produced or imported, at each time slice must be greater or equal to what is consumed or exported. The case of electricity will be treated in the module describing power distribution activities.

$$\forall t \in \Theta, s \in S, c \in C$$

$$
\sum_{l \in L, \ p \in P\_PROD[c] \cap P\_MAP[l]} (\mathbf{COM}[t, s, l, p, c] + \mathbf{IMP}[t, s, c]) \times \text{network\_efficiency}[c]
$$

$$
\geq \sum_{l \in L, p \in P\_CONS[c] \cap P\_MAP[l]} \mathbf{COM}[t, s, l, p, c]
$$
$$
+ \text{frac\_dem}[t, s, c] \times \text{demand}[t, c] + \mathbf{EXP}[t, s, c]
$$

Capacity Bounds Production For each technology, what is produced is bounded by the available capacity.

$\forall t \in \Theta, s \in S, c \in C, p \in \text{P\_MAP}[l]$

$$\sum_{c \in C\_ITEMS[flow\_act[p]]} \textbf{COM}[t, s, l, p, c]/\text{act}_f\text{lo}[p, c]$$

$$<= \text{avail\_factor}[t, s, p] \times \text{cap\_act}[p] \times fraction[s] \times$$

$$(\sum_{k \in 0...t:\text{life}[p] \geq k+1,\ t-k \geq \text{avail}[p]} \textbf{ICAP}[t-k, l, p] + \text{fixed\_cap}[t, l, p])$$

A.3.2 Balance Equations for Commodity Storage Between Time-Slices

For each storable energy, the amount of stored energy in a given timeslice is transferred to its successive timeslice with a reduction described by a loss factor `storage_loss-factor`.

$\forall t \in \Theta, c \in C_s, s \in S$

$$(\sum_{l \in L, p \in P\_PROD[c] \cap P\_MAP[l]} \textbf{COM}[t, s, l, p, c]) \times \text{storage\_loss-factor}[c]$$

$$= \sum_{l \in L, p \in P\_CONS[c] \cap P\_MAP[l], \sigma in SUCC[s]} \textbf{COM}[t, \sigma, l, p, c];$$

A.3.3 Activity bounds

Exogenously defined bounds on activity

$\forall t \in \Theta, s \in S, l \in L, p \in \text{P\_MAP}[l]$

.

$$\text{act\_bnd\_lo}[t, s, l, p] \leq \sum_{c \in C\_ITEMS[flow\_act[p]]} \textbf{COM}[t, s, l, p, c] \leq \text{act\_bnd\_up}[t, s, l, p]$$

A.3.4 Imports Bounds

Exogenously defined bounds on imports.

$\forall t \in \Theta, s \in S, c \in C$

$$\text{imp\_tot\_bnd\_lo}[t, c] \leq \sum_{s \in S} \textbf{IMP}[t, s, c] \leq \text{imp\_tot\_bnd\_up}[t, c]$$

A.3.5 Export Bounds

Exogenously defined bounds on exports.

$\forall t \in \Theta, s \in S, c \in C$

$$\text{exp\_tot\_bnd\_lo}[t, c] \leq \sum_{s \in S} \textbf{EXP}[t, s, c] \leq \text{exp\_tot\_bnd\_up}[t, c]$$

A.3.6 Capacity Bounds

Exogenously defined bounds on capacity.

$\forall t \in \Theta, l \in L, p \in \text{P\_MAP}[l]$

$$\text{cap\_bnd\_lo}[t, l, p] \leq \sum_{k \in 0\ldots t:\text{life}[p]\geq k+1 \,\&\, t-k\geq\text{avail}[p]} \mathbf{ICAP}[t-k, l, p] + \text{fixed\_cap}[t, l, p] \leq \text{cap\_bnd\_up}[t, l, p]$$

Investment Bounds

Exogenously defined bounds on investment.

$\forall t \in \Theta, l \in L, p \in \text{P\_MAP}[l]$

$\text{icap\_bnd\_lo}[t, l, p] \leq \mathbf{ICAP}[t, l, p] \leq \text{icap\_bnd\_up}[t, l, p]$

A.3.7 Peak Reserve Equations

Global reserve to cover peak load variations. These constraints impose that the total capacity of all processes producing a commodity at each time period and in each region must exceed the average demand in the time-slice where peaking occurs by a certain percentage. This constraint introduces a safety margin to protect against random events not explicitly represented in the model.

$\forall t \in \Theta, s \in S, c \in C$

$$1/(1 + peak\_reserve[t, s, c]) \times \Big(\sum_{l \in L, p \in P\_PROD[c] \cap P\_MAP[l]}$$
$$cap\_act[p] \times peak\_prod[p, s, c] \times fraction[s] \times avail\_factor[t, s, p] \times$$
$$\Big(\sum_{k \in 0..t:life[p] \geq k+1 \text{ and } t-k \geq avail[p]} \mathbf{VAR\_ICAP}[t-k, l, p] + fixed\_cap[t, l, p]\Big)$$
$$+ \sum_{l \in L, p \in P\_PROD[c] \cap P\_MAP[l]} peak\_prod[p, s, c] \times \mathbf{VAR\_COM}[t, s, l, p, c]$$
$$+ \sum_{l \in L} \mathbf{VAR\_IMP}[t, s, l, c]\Big) \times network\_efficiency[c]$$
$$\geq$$
$$\sum_{l \in L, p \in P\_CONS[c] \cap P\_MAP[l]} \mathbf{VAR\_COM}[t, s, l, p, c]$$
$$+ \sum_{l \in L} \mathbf{VAR\_EXP}[t, s, l, c]$$

Remark 3 This global reserve must be distinguished from the system reserve that we will introduce later on, when modeling the power distribution level, which has a role of coping with production variations intervening, in a fast time scale, due to intermittency of wind and solar generation.

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