FLEXIBILITY OF DRINKING WATER SYSTEMS: AN OPPORTUNITY TO REDUCE CO_2 EMISSIONS

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ABSTRACT
Drinking water systems (DWSs) are huge electricity consumers, mainly due to pumping operations. In these systems, electricity costs represent approximately one-third of the total operating costs. Because of the environmental impact of electricity generation worldwide (coal, gas, and diesel), water systems also implicitly contribute to global warming. However, these systems have flexibility thanks to water storage structures (tank and reservoirs) and variable speed pumps. The flexibility of DWSs is generally used to optimize energy costs. Furthermore, this flexibility can also be used to provide an environmental and operational service for the power system, by reducing peak power load and the volume of energy transactions on wholesale markets. Indeed, peak power reduction can be sold by water utilities on electricity markets, preventing the production of an equivalent amount of additional energy. In France, peak hours require a massive use of fossil energy sources, which makes electricity production at these periods extremely expensive, both economically and ecologically. Using a mathematical optimization model, we optimize the management of these peak periods by shifting load at off-peak hours and selling the reduced energy on the French wholesale energy market. In this paper, we explore the ecological benefits that water systems could provide through this optimization process. We evaluate the CO_2 emissions that can be effectively reduced on three real DWSs in France. For these three systems, avoided CO_2 emissions were estimated at 2,190 kg/day for the largest system and 194 kg/day for the smallest one, which is equivalent to the emission of 145–1620 cars during 10 km of driving. We also evaluate, based on some hypotheses, the potential for CO_2 reduction from water systems at the French scale.
Keywords: CO_2 emissions, demand response, drinking water systems, peak energy load.

1 INTRODUCTION

Global warming is one of the major challenges facing the world today. Carbon emissions from fossil combustion are considered among the main factors causing global warming [1]. Because of the harmful consequences of this phenomenon on the future of the world, this subject is often a part of the political, diplomatic, economic as well as academic concerns [2].

The electricity sector, still highly dependent on fossil fuels, is one of the main contributors to global warming. In fact, fossil generation units contribute up to 65% of the world total electricity production: 38% for coal, 23% for natural gas and 4% for oil [3]. Alarmed by the actual situation and wishing to contribute to energy sobriety, some countries around the world have launched energy transition programmes. These programmes mainly focus on increasing production from renewable sources and limiting as much as possible dependence on fossil fuels. However, the progressive integration of renewable energies raises the problem of their effective integration into the power networks. The intermittency of these energies requires additional efforts to manage the physical equilibrium in real time between load and generation. It is in this context that the notion of demand response (DR), defined as the change in the power consumption of an electric utility in response to a given signal, is important. Industrial processes are believed to be the best candidates for DR, especially the ones having some storage units. They can adapt their energy consumption to the power system needs, in a return of a remuneration [4]. In this article, the drinking water industry, which is a major electricity consumer, is considered.

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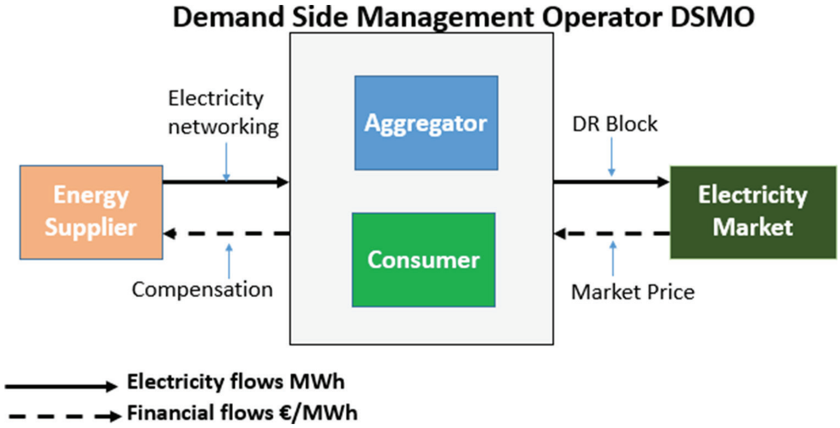


Figure 1: Energy blocks and financial flows exchange for NEBEF.

In many countries, transmission system operators and regulatory agencies have put in place some mechanisms to encourage DR integration in energy markets. In France, DR operators, which are generally independent operators aggregating the flexibility of several energy consumers, are in competition with energy suppliers to value the flexibility of consumers. They can therefore trade DR energy directly on electricity markets without prior agreement of suppliers [5]. This opportunity offered to encourage DR operators has been accompanied by important regulatory work to define the rules and modalities for the exchange of financial and energy flows between different market players.

Since 2014, DR can be traded in the French spot power market as a resource, under a mechanism called 'NEBEF mechanism' [6]. This mechanism allows DR operators to sell, at day D-1 at midday, the energy that would not be consumed on day D by the consumer, and to financially compensate the supplier of the site participating in the mechanism [6]. In other words, the DR operators buy the energy from the supplier at a regulated 'compensation' price, and sell it later on, in agreement with the consumer reducing his power consumption, on the energy market at the market price (Figure 1). The difference between spot price and compensation price represents the economic benefit for DR from the market transaction.

For a DR programme through the NEBEF mechanism, each bid must constitute at least 100 kW of power reduction. Furthermore, DR bids cannot exceed 2 h per bid. Finally, the estimation of the real load reduced during a DR event is done by the French transmission system operator, RTE, comparing the 'reference curve' and the 'DR curve'. The reference curve is the minimum between the mean electric load just before and just after the DR event, over a period equal to that of the DR event [6].

2 DRINKING WATER SYSTEMS

Drinking water systems (DWSs) are designed to produce, transport and distribute water from water sources to consumption areas. These systems generally include water production plants, storage units such as tanks and reservoirs, connection elements such as pipes and pumping stations, including fixed and variable-speed pumps.

2.1 Energy flexibility

DWSs are known to be highly energy-dependent, accounting for up to 5% of a city's electricity consumption [7]. Pumping operations represent approximately two-thirds of this electricity consumption [8]. Storage units such as tanks and reservoirs provide some flexibility that can be exploited for securing water supply and optimizing the pump scheduling [9]. Indeed, these storage units are generally used by water operators to store water at off-peak periods when electricity prices are low. However, peak periods with high energy prices experience minimized pumping operations to meet water demands at minimum cost. DWSs flexibility is increasing with the size of tanks: the larger a tank is, the more it has flexibility for operational management [10]. Water tanks and reservoirs can thus be assimilated to electric batteries because they implicitly allow for electricity storage [10]. Furthermore, variable-speed pumps can adapt their flow rate and energy consumption to the needs, providing additional flexibility to DWSs [11].

2.2 Operational management

The daily operation of DWSs is performed by water system operators. The dispatching centre is in charge 24 h a day for the proper functioning of water system equipment. This operational management of DWSs is subject to several constraints that can be summarized as follows [10]:

- Physical constraints: correspond to storage minimum and maximum operational filling level of tanks and reservoirs, as well as the maximum flow rate that can pass through a pipe.
- Regulatory constraints: refer to qualitative and quantitative conditions imposed by public authorities on the use of water resources.
- Mass balance constraints: by neglecting compressibility effects and using steady-state approximations of hydraulic conditions, they impose the equality between the sum of the incoming flows and the sum of the outflows at each network node.
- Hydraulic constraints: correspond to the fundamental equations for pipes, called the head-loss equations. These equations translate the energy losses that water undergoes by its passage in the pipelines.
- Operational constraints: correspond to the particularities of each water system functioning. A detailed review of these kinds of constraints is described in [12].

These constraints are very often discussed in the literature regarding pump scheduling in water systems. We will refer to them as the DWS classical constraints.

3 MODELING ASPECTS

In this section, we first describe a model of DR in the French spot power market for DWSs. Then, CO_2 emissions avoided by a DR programme are estimated, based on the French spot market context.

3.1 DR for water systems management

We model the optimal DR bidding strategy for DWSs on the French spot power market, through the NEBEF mechanism. We consider only the time slot 18:00–20:00 for DR participation, since it corresponds to French daily peak period in winter when the power system needs DR to replace the high-cost high-emissions peak generation units. The planning horizon used is 24 h starting at 06:00 and the time step is set to 1 h. We consider that the water utility perfectly anticipates spot market prices and that the main issue is to decide whether to bid on the market or not. The modelling approach used in this section is mainly derived from our previous work [9], [10].

We consider the following notations for the problem formulation:

- $x_{i,t}$ is the state of pump at period t
- $c_{i,t}$ the electric cost in € when pump i is on at period t
- $P_{i,t}$ the power activated by pump at period t
- P^{DR} the DR power in kW put on sale on the spot market for the period 18:00–20:00
- $P^{\mathrm{DR}}_{\min}$ the minimum DR bid allowed for NEBEF (in kW)
- r the market spot price for the period 18:00–20:00 (in €/kWh).
- ρ the compensation price at period t (in €/kWh)
- t^{DR} the DR period, 18:00–20:00
- t^{ref} the reference periods, 16:00–18:00 and 20:00–22:00

The optimization problem related to minimizing pumping costs while maximizing the benefits earned from trading DR energy on the spot market could be written as follows:

$$\text{Minimize} \sum_{i.t} C_{i,t} \cdot x_{i,t} - P^{\mathrm{DR}} \cdot (r - \rho)$$

subject to:

$$\begin{cases} \text{DWS Classical Constraints} \\ P^{\mathrm{DR}} \geq P^{\mathrm{DR}}_{\min} \\ \forall t_1 \in t^{\mathrm{ref}}, \forall t_2 \in t^{\mathrm{DR}} : \sum_i P_{i,t_1} x_{i,t_1} \geq \left(\sum_i P_{i,t_2} x_{i,t_2} + P^{\mathrm{DR}} \right) \end{cases} \qquad (P_1)$$

3.2 CO_2 savings from DR participation

In France, more than 72% of the electricity is produced from nuclear energy, while fossil fuels contribute to only 9% of the country's total electricity production [13]. These fossil production plants, known as French peak generation units, are used to respond to rapid changes in electricity demand and to manage peak demands. Their fast mobilization time allow them to be a flexible source of electricity production.

On the demand side, France is a thermo-sensitive country, meaning that electricity demand is highly driven by weather conditions. According to the French transmission system operator, RTE, a decrease of 1°C of temperature in winter between 18:00 and 20:00 hours implies an increase of 2,300 MW in electricity consumption [14]. Figure 2 shows the CO_2 emissions per kWh of energy produced for 2 days in France. It is observed that more than 42% of CO_2 is emitted in winter when compared to spring [15].

Transactions in the French spot market are based on the merit-order principle, meaning that the supply curve is constructed by aggregating bids in ascending order according to their operational cost. Renewables have a very low marginal cost and are found at the bottom of the market's supply curve. Nuclear energy also has a low operating cost and follows the renewables in the ranking.

Peak power plants, starting with coal-fired power plants, then combined cycle gas plants and ending with diesel or gasoline fuels, have the highest running cost. Figure 3 illustrates the merit-order principle and shows how DR could replace peak generation productions. In Figure 3, a peak day is considered with a compensation price of 56.1 €/MWh. Two supply curves on the market are considered: one with DR and the other without DR. In the one without DR, block 4, corresponding to a combined cycle gas power generation bid, balanced the market with a marginal price of P*. With DR, the DR block 4' put for sale with a price of P*' < P*, replaced block 4 according to the merit-order principle and led

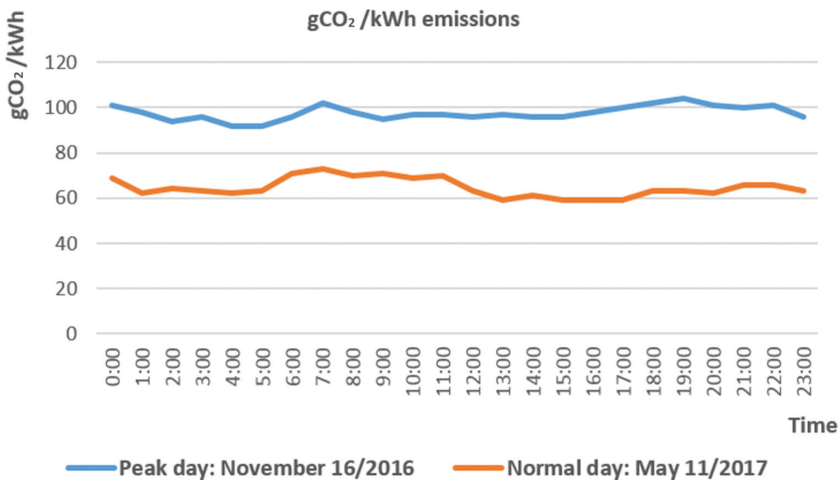


Figure 2: CO_2 emissions in grams/kWh for 2 days in France.

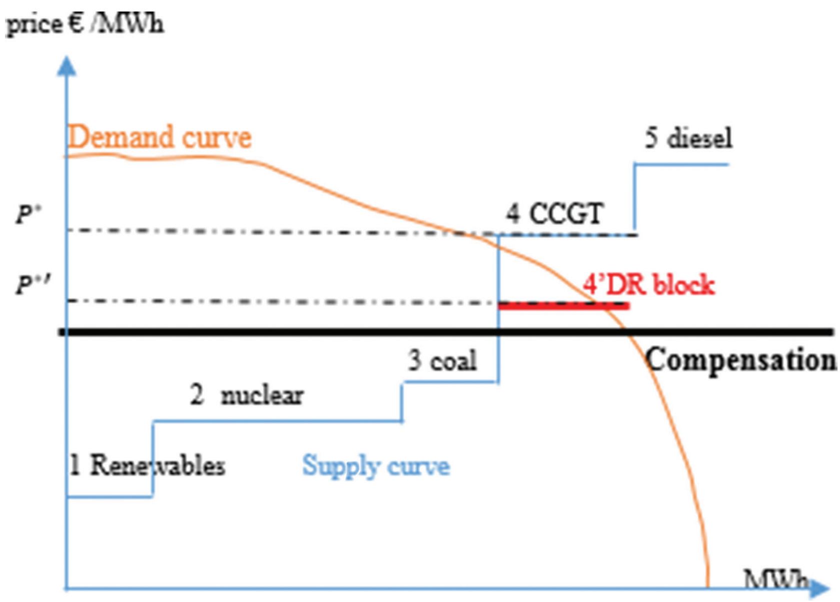


Figure 3: Merit-order principle and DR impact on the supply curve.

to a new market price P*' < P*. The DR block 4 would be inserted between two peak generation unit blocks, depending on the DR bid price and peak generations unit variable cost. In addition, it could also lower market price if the DR bid is competitive (large volume).

The ecological study conducted in this article is based on the assumption that each DR power bid sold on the spot market is a complete substitution of an equivalent power coming from a fossil generation unit. The objective is to estimate the avoided CO_2 emissions from DWSs participation in the DR programme. Since it is difficult to estimate which of the fossil production technologies is replaced by each DR block sold on the market, the average contribution of

Table 1: Contribution of peak generation technologies to CO_2 emissions in France.

Peak generation technology	Grams CO_2/kWh
Coal	956
Gas	800
Fuel	360
Weighted average 2016	486

French peak generation units to CO_2 emissions is considered, weighted by their utilization rates during the year 2016. Table 1 shows the CO_2 emissions by coal, gas and fuel production plants in grams per kWh produced in France, as well as their weighted average CO_2 emissions.

In this article, each kWh of DR energy sold on the spot market is assumed to avoid the emission of 486 g of CO_2.

4 NUMERICAL RESULTS

4.1 Benchmark water systems

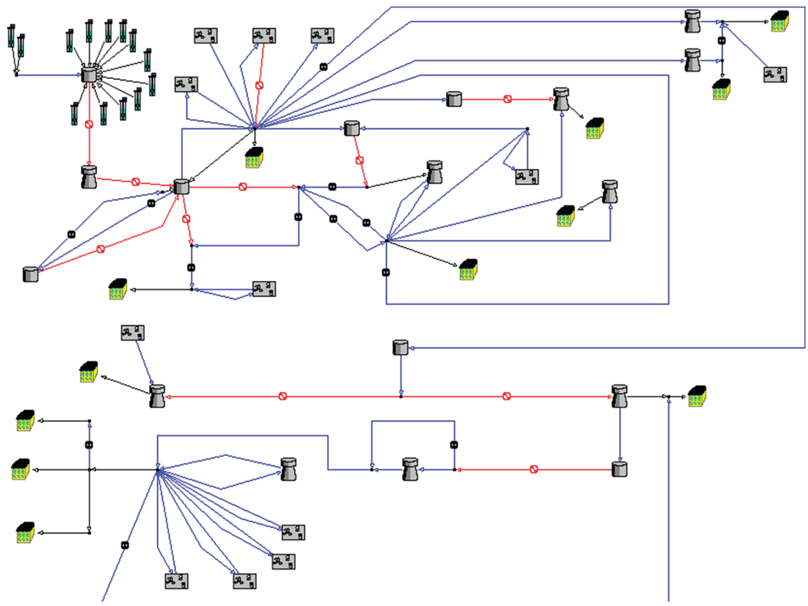
Numerical results are discussed based on three water systems in France, whose physical models are presented in Figure 4.

- System 1: This is a water system that only supplies residential areas. It is located in a mountain area with significant elevations in the distribution scope, which makes energy consumptions very high. In 2012, its power consumption was 8 GWh with a cost of around 550,000 €.
- System 2: This is a small system with an average daily water demand of around 10,000 m^3. Energy consumption is low for this system because of the small distances from water sources to consumption areas.
- System 3: This is the largest system among the three studied because of its physical size and the associated water demand. This system only supplies residential areas. It contains a main pumping station used to raise water after its capture on a height of more than 110 m.

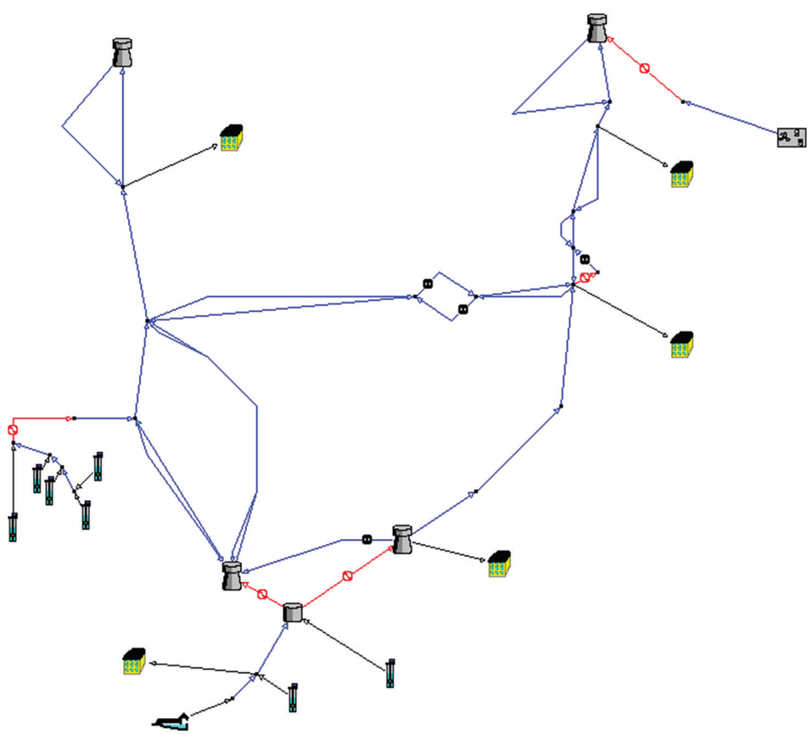
4.2 CO_2 emissions avoided by three real water systems in France

Optimization problem (P_1) was solved considering the compensation price and the average French spot price between 18:00 and 20:00 hours for October, November and December 2016. The compensation price is equal to 56 €/MWh and the average spot price is equal to 88 €/MWh. Figure 5 shows the optimal power consumption of each water system for a day with DR participation. It is observed how energy consumption is minimized during the DR period. However, reference periods experience high energy consumption in anticipation of the DR event. Table 2 shows the main results of optimal DR bid strategies resulting from the optimization approach, and the estimated CO_2 savings.

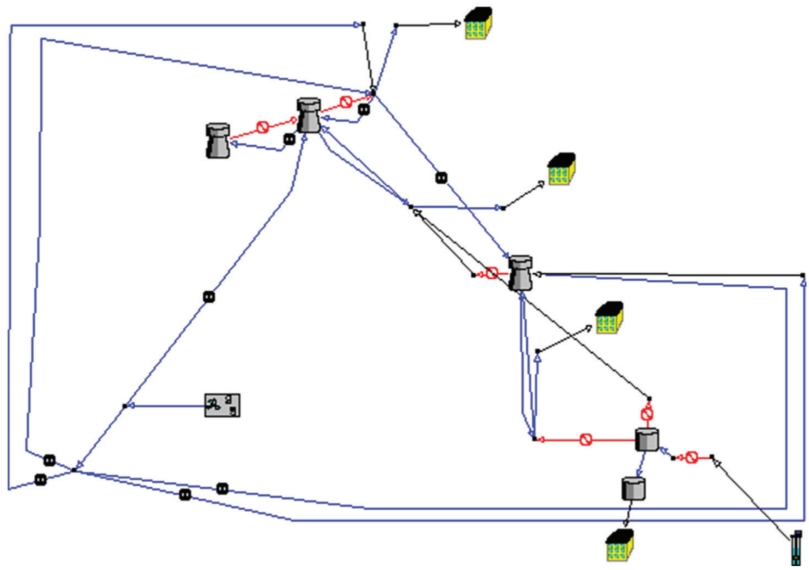
As shown in Table 2, System 3 contributes to the reduction of 2,190 kg of CO_2 per day, while System 2 contributes to the reduction of 194 kg of CO_2. The advantage of the proposed model is that, in addition to significant CO_2 savings, water systems realize economic gains on their electricity bills by selling DR energy blocks on the market.



(a): System 1

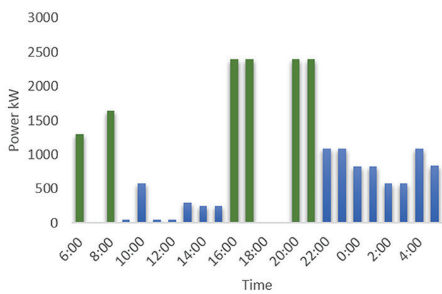


(b): System 2

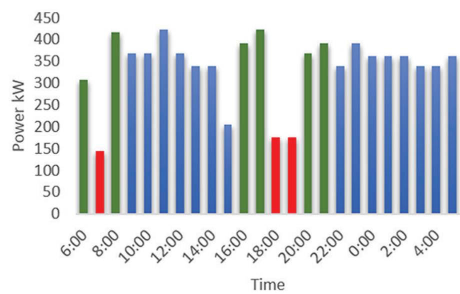


(c): System 3

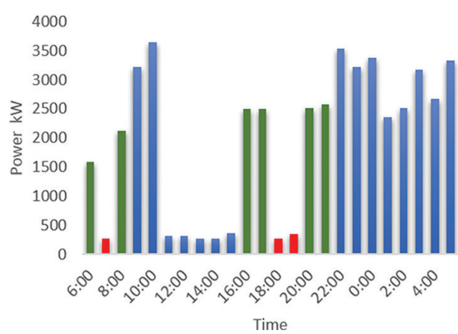
Figure 4: Physical model of three real water systems in France.



(a): System 1



(b): System 2



(c): System 3

Figure 5: Optimal power consumption with DR consideration.

Table 2: Optimal DR strategies for three French water systems.

	System 1	System 2	System 3
Water demand in m^3	13,000	10,075	61,920
DR power in kW	1,890	200	2,254
DR energy in kWh	3,780	400	4,508
CO_2 avoided in kg	1,837	194	2,190

In order to have an indicator allowing us to compare the three water systems regarding ecological performances, a normalization of CO_2 savings by water demands is necessary.

As shown in Table 3, System 1 is the largest contributor to CO_2 reductions per m^3 of water because of its high energy consumption comparing to its water demand.

4.3 CO_2 emissions avoided by water systems in France

To highlight the importance of water system participation in the DR program, we propose to estimate the DR NEBEF potential at the French scale. The approach considered consists on extrapolating the results obtained for the three experimental systems, under some assumptions.

In France, the daily average water consumption of a person is around 140 L [16], which gives, for all the country, a daily consumption of $d = 9{,}100{,}000$ m^3. However, each water system has its own flexibility and constraints and it is difficult to perform a direct extrapolation of the previous results. The assumption made in this section is that each French water system is comparable to one of the three previous systems. We then distinguish the three following types of water systems:

- Type #1: systems located in mountainous areas, same features as the System 1.
- Type #2: small systems intended to supply water to small municipalities, same features as System 2.
- Type #3: same features as System 3.

Let x, y and z three positive real numbers between 0 and 1 such that $x + y + z = 1$. The coefficients x, y and z correspond, respectively, to rates of French water systems of Type #1, 2 and 3. The approach for estimation of CO_2 savings in France for water systems is as follows:

- French daily water demand is decomposed into three parts d^1, d^2 and d^3, by multiplying the value 9,100,000 by x, y and z. Each part represents the contribution to each type of systems to the total water demand in France. For example, for $x = 0.05$ the Type #1 systems contribute daily to the production of 455 000 m^3 of water.
- Multiplication of normalized values of CO_2 and d^i for $i = 1,2,3$.

Table 3: Normalized CO_2 emissions avoided per m^3 for three water systems.

	System 1	System 2	System 3
Water demand in m^3	13,000	10,075	61,920
CO_2 savings in kg	1,837	194	2,190
CO_2 savings in kg/m^3	0.14	0.02	0.03

Table 4: Reduced CO_2 by French water systems for $x = 0.05$, $y = 0.2$ and $z = 0.75$.

	Type #1	Type #2	Type #3
CO_2/m^3	0.14	0.02	0.035
Demand d^i by type of systems (m^3)	455,000	1,820,000	6,825,000
CO_2 savings by type of systems (tons)	65	35	241

Table 5: Reduced CO_2 by French water systems for $x = y = 0.1$ and $z = 0.8$.

	Type #1	Type #2	Type #3
CO_2/m^3	0.14	0.02	0.035
Demand d^i by type of systems (m^3)	910,000	910,000	7,280,000
CO_2 savings by type of systems (tons)	128	17	258

Based on the demographic and topological distribution in France, we can assume that DWSs in mountainous areas (Type #1) contribute at most 10% of total French water consumption. Similarly, it is assumed that small systems like System 2 contribute at most 20% of total French consumption.

Since System 1 is the largest contributor to CO_2 reductions per m^3 of water and System 2 the lowest one, the maximum value of estimated CO_2 savings is obtained for $x = 0.1$ and the minimum is obtained for $y = 0.2$. Table 4 and 5 represent, respectively, an estimation of minimum and maximum CO_2 savings by French water systems.

Based on the assumptions made in this section, DWSs in France can contribute to the reduction of 341–403 tons of CO_2 per day by participation in the NEBEF mechanism, while generating economic gains on their electricity bills. This reduced amount of CO_2 is the equivalent of emissions from 243,000 to 289,000 French cars during 10 km of driving [17].

5 CONCLUSION

The flexibility of DWSs can be optimized to reduce CO_2 emissions, known to be harmful for the environment. Minimizing energy consumption during French winter peak periods could reduce the use of fossil fuel productions to deal with these peaks. Through a linear programming model and based on some assumptions, significant savings of CO_2 emissions from water systems participation in a French DR program have been estimated in this article.

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