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ORIGINAL PAPER

Peak shaving: a planning alternative to reduce investment costs in distribution systems?

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Abstract

In the future, the foreseen increase of residential electricity consumption will force the Distribution System Operators to reinforce their networks at great expense. Through the emergence of ICT solutions and the increase of electric consumption flexibility at residential level, peak shaving has become an interesting alternative for reducing the investment costs in a distribution grid facing a load increase. This can be achieved with energy management systems (EMS) installed at residential level. Specifically, this work aims at considering peak shaving as an alternative to network reinforcement in a 20-year distribution planning study. For this purpose, the present work incorporates an optimal peak shaving approach to an accurate Convex DistFlow-based planning approach. Based on this, it quantifies how peak shaving can economically compete with network reinforcements for 12 real UK distribution networks under various flexibility scenarios. The results highlight that peak shaving is a competitive alternative to line reinforcement if the maximum initial line loading at the initial year of the planning study is under 80% of its nominal thermal rating value. It is also shown that EMS devices with a cost between 10 and 250 £/unit are economically competitive with network reinforcements depending on the considered network. Finally, this work proposes a planning decision metric, the initial line loading (ILL), measured at the beginning of the planning study, on the basis of which reinforcement decisions can be made.

Keywords Distribution planning · Energy management system · Flexibility · Peak shaving

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1 Introduction

Electricity consumption in Europe has been stagnating in recent years, notably due to improvements in energy efficiency in various sectors such as household appliances and industry. However, the willingness to decarbonise economy is triggering an ever increasing electrical consumption from residential and industrial levels. At residential level, the energy vector for both heating and transportation begins to shift from various fuels to electricity with the use of thermo-electrical systems (e.g. heat pumps) and electric vehicles respectively. In the UK for example, the penetration of these two technologies could increase the current domestic electricity demand by up to 48% by the year 2030 [1].

This dramatic increase of residential electricity consumption will force the distribution system operators (DSO) to reinforce their networks to cope with larger power flows. Network reinforcement, if done in a classic way, is very expensive as it implies to increase the distribution capacity by adding new lines. However, the problem is partly the solution. As a matter of fact, domestic flexible devices such as domestic battery, thermo-electrical systems or electric vehicles offer a real potential for flexibility. In particular, their flexibility may be used to shave the electricity consumption peak by spreading the same consumption of energy over a longer time period. As peak power is the determining factor for network sizing, the use of flexibility can decrease the need for network reinforcement.

1.1 Literature review

1.1.1 Planning

The goal of a reinforcement planning study is to find the cheapest set of investments to be made in the network in order to satisfy technical and operational constraints while accommodating increasing power flows. These investments are related to transformers, distribution lines and fault protection. In this paper, we only consider investments in distribution lines. There are three types of decisions to be made, i.e. the size, location and timing of investments. This is a multi period optimization problem that can be conceptualized as follows:

$$\begin{aligned} \underset{\text{size, timing, location}}{\text{minimize}} \quad & \text{Investment costs} \\ \text{subject to} \quad & \text{Power flow equations} \\ & \text{Power balance at each node} \\ & \text{Voltage bounds at each node} \\ & \text{Line thermal rating} \end{aligned}$$

As stated in [2], most distribution system planning related works have focused on heuristics in order to tackle larger problems. However, heuristics present several shortcomings. First, the optimality of their solutions may not be proved. Then, if the optimization is stopped before convergence due to a restriction on the computation

budget, they do not deliver any evaluation of the distance to optimality (the optimality gap). Finally, they are mainly used in academic studies and are not often used in the industry.

In the recent years, significant progress has been made both in convex relaxations of power flows [3] and mathematical programming solvers. In this paper, we propose a reinforcement planning approach based on the Convex DistFlow relaxation of power flows first proposed in [4]. It is a Second Order Cone relaxation of power flow equations which is proven to be exact for radial networks under mild theoretical conditions regarding power injections, voltage bounds and line impedances [5]. Furthermore, it is shown that it is exact or close to exact in numerous practical cases [6].

As mentioned above, this may be very expensive as lines should be sized to accommodate higher peak currents. This is especially the case in underground LV networks for which trench excavation for cable replacement/addition incurs significantly higher costs compared to overhead lines.

Hence, there is more and more interest for alternative solutions avoiding expensive network reinforcements. These are broadly grouped under the term "Active Network Management " (ANM). ANM consists of implementing operational strategies to make the most of the existing network capacity before having to increase it [7]. These strategies may be classified in two categories. The first one concerns network participants and encompasses demand side management (DSM), control of storage elements and dispatch/curtailment of distributed generation (DG) units while the latter corresponds to network elements and gathers network reconfiguration and Volt/Var control.

Reference [8] belongs to the first category, as the authors investigate how the integration of distributed generation can defer the need for investments in lines and substations. In the same category, an innovative market-based approach consistent with an unbundled electric power sector is presented in [9]. In this paper, the authors propose an auction-based market where prosumers can sell their flexibility (DSM, storage, DG units) to the DSO who is willing to use it in order to reduce its costs for reinforcing network assets. The second category includes [10] which states that distribution automation, i.e. monitoring and remote switching of network elements helps reducing operational margins and hence make a better use of existing assets.

Then, some authors consider both categories. In [7], the authors show how three different ANM strategies (voltage control, power factor control and energy curtailment) can significantly increase the hosting capacity of an existing network for RES-based DG and avoid expensive reinforcements. In [11], the authors summarize ANM strategies and their scope of application depending on the goal pursued, e.g. losses reduction, voltage profile management or reliability enhancement. They also propose a framework to integrate ANM in distribution planning by considering it before investigating traditional grid reinforcement options. Finally, in [12], the authors propose a comprehensive modelling framework to integrate operational decisions into the reinforcement planning process. They present several formulations of the problem (Linear, Quadratic) and also extend these formulations to account for uncertainty in consumption and RES-based DG.

Nowadays, there is an increase in the flexibility available at residential level thanks to battery energy storage system, electric vehicles (EVs) and thermo-electrical loads such as heat pumps. However, none of the aforementioned papers investigated how

the use of this flexibility could help to decrease the peak consumption and thereby reduce the need for network reinforcements. In this paper, we consider the use of energy management systems (EMS) to perform peak shaving, i.e. reduce the stress on a utility network by decreasing the peak demand using controlled flexibility [13–15].

1.1.2 Peak shaving

Many recent studies have considered the use of residential flexibilities for peak shaving. Specifically [14–19], study the usage of batteries [20–22], consider the EVs and [16,23,24] integrate thermo-electrical loads e.g. heat pumps or electrical heaters, as source of flexibilities for peak shaving.

A number of studies focus on incentive schemes/pricing and control algorithms for peak shaving. Specifically [13,16,25,26], implement time-differentiated rates while [17,19,21–24] consider direct control with incentives payments.

Time-differentiated electricity rates are classified into time of use (TOU), known to user well in advance, i.e. months ahead for a long period [27–29], and dynamic pricing with different time granularity i.e. minutes or hours block and known to customers in advance. Among the different dynamic pricing, Real time pricing (RTP) aims at reflecting the actual generation costs of electricity to the customers on an hourly or sub hourly basis while Critical Peak Pricing (CPP) considers additional cost during high demand peak on a small fraction of the days in the year in order to encourage load shifting and shedding.

With incentive payments, the customer allows the central entity e.g. utility or aggregator, to control its loads according to a pre-defined agreement in exchange of incentives. There are different strategies developed to control residential loads using direct load control (DLC) or large industrial load using interruptible load management (ILM) [29]. In literature, these control approaches are implemented using different algorithms: quadratic (QP) [22], dynamic (DP) [17] and linear programming (LP) [19,21,23,24], in function of the considered flexibilities and their associated models.

These studies (Table 1) highlight a large dispersion of peak shaving results: from 5 to 50% [14,16,17,19,21–26]. As shown by the results, this potential is highly dependent on the conditions, i.e. electrical demand, temperature, and irradiation, the available flexibility, and the implemented peak shaving approach [14].

Given these results, this work considers three realistic peak shaving capabilities: 10, 20, and 30%. The peak shaving approach implemented in this paper considers a direct load control using an optimal peak shaving algorithm with perfect forecasts. The houses are equipped with the associated flexibilities, batteries, EVs and heat pumps, according to the considered peak shaving reduction, taken as a parameter in this study.

1.2 Contribution

The literature review has shown the lack of studies considering peak shaving as a planning alternative for distribution network reinforcement. The present paper implements such an approach with an accurate Convex DistFlow-based planning model

Table 1 Literature review of peak shaving approaches

References	DR tariff/algorithm	Peak reduction
Time-differentiated electricity rates		
[16]	RTP	[20, 25] %
[25]	TOU	5 %
[25]	CPP	15 %
[26]	TOU	[34,40]%
Incentive payments		
[14]	LP	50%
[17]	DP	12.5%
[19]	LP	30%
[21]	LP	10%
[22]	QP	[26, 30]%
[23]	LP	N.A.
[24]	LP	N.A.

and an optimal peak shaving implementation. The contribution of this work can be summarized as:

- Quantification of the competitive costs of individual home energy management systems (EMS) considered as a planning alternative to line reinforcements for 12 different distribution grid topologies and under different peak shaving reduction scenarios: 10, 20, and 30%.
- Problem formulation based on the combination of (i) a state-of-the-art planning model proven to be exact or close to exact in numerous practical cases and (ii) an optimal peak shaving approach.

Thanks to this, this paper answers to these fundamental questions:

1. Is it possible to identify a decision planning metric which determines if reinforcement is needed for a particular line? How is it impacted by the use of flexibility?
2. What would be the maximum EMS cost to compete with line reinforcement?

The article is organized as follows: Sect. 2 formalizes the reinforcement planning optimization and the peak shaving used as a planning alternative. Section 3 describes the case study: distribution network considered, load profiles and considered parameters. Section 4 presents the comparison metric and discusses the results under different conditions.

2 Problem formulation

2.1 Reinforcement planning model

Distribution network planning includes integer decision variables representing the size, location and timing of the investments being made as well as continuous variables such as power flows, voltages and currents which makes it a Mixed-Integer Program.

Power flow equations at the heart of the problem are non-linear and non-convex which makes it difficult to solve and prevents from proving global optimality. The model we use in this paper has been presented in a previous publication [30] and is a convex relaxation of the original problem. More precisely, it is based on the Convex DistFlow formulation. As stated in the introduction, this formulation is exact or close to exact for many practical cases. This model can thus be cast as Mixed-Integer Second Order Cone Program (MISOCP). We begin by defining the various sets, parameters and variables of the model.

A. Sets and related indices

$\mathcal{V}: \ i \in \mathcal{V}$	Set of vertices of the network
$\mathcal{E}: \ (i, j) \in \mathcal{E}$	Set of directed edges representing allowed lines location in the network
$\mathcal{L}: \ l \in \mathcal{L}$	Set of reinforcement states for a line: l=1 corresponds to the situation without reinforcement, $2 \leq l$ correspond to different reinforcement levels
$\mathcal{T}: \ t \in \mathcal{T}$	Set of hourly timesteps

B. Parameters

$n = \text{card}(\mathcal{V})$	Amount on nodes in the network
$L = \text{card}(\mathcal{L})$	Amount of different reinforcement levels
D_{ij}	Distance between nodes i and j
P^C_{it}, Q^C_{it}	Active and reactive power consumption at node i at timestep t
r_l, x_l	Resistance and reactance per unit length for reinforcement decision l
$\overline{S}_l$	Maximum apparent power for line type l
$\underline{v}, \overline{v}$	Min. and max. admissible voltage
$C_{reinf,l}$	Cost of reinforcement option l per unit length

C. Variables

p_{ijt}, q_{ijt}	Active and reactive power flow between nodes i and j at timestep t
w_{it}	Squared voltage amplitude at node i at timestep t
l_{ijt}	Squared current amplitude on line (i, j) at timestep t
$\lambda_{ijl} \in \{0, 1\}$	Boolean variable representing the fact that the reinforcement option l is chosen (1) or not (0)

We present the model hereunder. The objective is to minimize the sum of investment costs (CAPEX). We consider for each branch L possible discrete levels of reinforcement.In these expressions, λ_{ijl} is a binary variable defined for each branch (i, j) with $l \in \{1 \ldots L\}$ indicating whether a reinforcement is made for the branch (i, j) or not, $l = 1$ corresponding to the base case (no reinforcement) and $l > 1$, k being a positive integer, corresponding to different levels of reinforcement. p_{ijt} is the active power flow between nodes i and j at period t. The parameters are the following: $C_{reinf,l}$ is the cost of the level l reinforcement(€/km) and D_{ij} is the distance between nodes i and j (km)).

$$\min_{\lambda} \sum_{(i,j),l \in \mathcal{L}: l>1} \lambda_{ijl} C_{reinf,l} D_{ij}$$

Variables representing the different levels of investments (none = level 1,…, level L) cannot be different from 0 simultaneously as it would represent that we simultaneously reinforce and do not reinforce the line for example. Hence, they must sum to 1, which is expressed in Eq. (8). Equation (2) expresses that a reinforcement decision affects a given in both directions.

$$\sum_{l\in\mathcal{L}} \lambda_{ijl} = 1 \quad \forall (i,j) \in \mathcal{E}, l \in \mathcal{L} \tag{1}$$

$$\lambda_{ijl} = \lambda_{jil} \quad \forall (i,j) \in \mathcal{E}, ki : (i,j) \in \mathcal{E}, l \in \mathcal{L} \tag{2}$$

Equations (3)–(6) express the conservation of active and reactive power at the transformer and at all load points. $P_{1,t}$ and $Q_{1,t}$ are the active and reactive power coming from the distribution transformer at each timestep, while P_{Cit} and Q_{Cit} are the active and reactive power consumptions at every load point and for every timestep.

$$P_{1,t} = \sum_{(i,j)} p_{1jt} \quad \forall j \in \mathcal{V}, t \in \mathcal{T} : (i,j) \in \mathcal{E} \tag{3}$$

$$Q_{1,t} = \sum_{(i,j)} q_{1jt} \quad \forall j \in \mathcal{V}, t \in \mathcal{T} : (i,j) \in \mathcal{E} \tag{4}$$

$$-P_{Cit} = \sum_{(i,j)} p_{ijt} \quad \forall (i,j) \in \mathcal{E}, t \in \mathcal{T} \tag{5}$$

$$-Q_{Cit} = \sum_{(i,j)} q_{ijt} \quad \forall (i,j) \in \mathcal{E}, t \in \mathcal{T} \tag{6}$$

Constraints (8)–(13) express the physics of power flows. l_{ijt} represents the squared amplitude of line current and w_{it} represents the squared voltage amplitude. Equation (7) states that the amplitude of the current is the same in both directions for a given line. Equation (8) expresses the fact that power flowing in a line is the product of node voltage and line current. It is relaxed as an inequality and has the form of a (convex) rotated second order cone constraint. This is the only relaxation in this SOC model. If this inequality is binding for all indexes (i.e. the right-hand side is equal to the left-hand side), then there is no relaxation gap and the relaxed problem is exact.

$$l_{ijt} = l_{jit} \quad \forall (i,j) \in \mathcal{E}, t \in \mathcal{T} \tag{7}$$

$$p_{ijt}^2 + q_{ijt}^2 \leq w_{it} l_{ijt} \quad \forall (i,j) \in \mathcal{E}, t \in \mathcal{T}. \tag{8}$$

Equation (9) expresses active losses and is written such that the only active constraint is the one corresponding to the actual state of reinforcement of the line between *i*and j (i.e. to the unique l such that $\lambda_{ijl} = 1$, in order to avoid bilinear terms. Thus, r_{ijl} represents the resistance per unit length of the line (i,j) depending on the level of reinforcement l. The reactive losses on the line are similarly developed by replacing p_{ijt} and r_{ijl} by q_{ijt} and x_{ijl} respectively (Eq. (10)).

$$-(1-\lambda_{ijl})r_l D_{ij}\frac{\overline{S}_\Lambda^2}{\underline{v}^2} \le p_{ijt}+p_{jit}-r_l D_{ij} l_{ijt} \le D_{ij}\max_l(r_l\overline{S}_l^2)\frac{1}{\underline{v}^2}(1-\lambda_{ijl})$$
$$\forall (i,j)\in\mathcal{E}, l\in\mathcal{L} \tag{9}$$

$$-(1-\lambda_{ijl})x_l D_{ij}\frac{\overline{S}_\Lambda^2}{\underline{v}^2} \le q_{ijt}+q_{jit}-x_l D_{ij} l_{ijt} \le D_{ij}\max_l(x_l\overline{S}_l^2)\frac{1}{\underline{v}^2}(1-\lambda_{ijl})$$
$$\forall (i,j)\in\mathcal{E}, l\in\mathcal{L}. \tag{10}$$

Equations (11)–(12) force active and reactive losses to be positive on every line. While being redundant, these constraints considerably tighten the resulting model.

$$p_{ijt}+p_{jit}\ge 0 \quad \forall (i,j)\in\mathcal{E}, t\in\mathcal{T} \tag{11}$$
$$q_{ijt}+q_{jit}\ge 0 \quad \forall (i,j)\in\mathcal{E}, t\in\mathcal{T}. \tag{12}$$

Equation (13) expresses voltage drops and is written in a way similar to (9) and (10). Equation (14) expresses voltage bounds at every node.

$$\begin{aligned}(1-\lambda_{ijl})&\left[\underline{v}^2-\overline{v}^2-2D_{ij}\overline{S}_\Lambda(r_l+x_l)-D_{ij}^2(r_l^2+x_l^2)\frac{\overline{S}_\Lambda^2}{\underline{v}^2}\right]\\ &\le w_{jt}-w_{it}+2D_{ij}(r_l p_{ijt}+x_l q_{ijt})-D_{ij}^2(r_l^2+x_l^2)l_{ijt}\\ &\le (1-\lambda_{ijl})\left[\overline{v}^2-\underline{v}^2+2D_{ij}\overline{S}_\Lambda(r_l+x_l)\right]\\ &\quad\times\forall (i,j)\in\mathcal{E}, t\in\mathcal{T}\end{aligned} \tag{13}$$

$$\underline{v}^2\le w_{it}\le\overline{v}^2 \qquad \forall i\in\mathcal{V}, tin\mathcal{T} \tag{14}$$

Equations (15) and (16) describe the line thermal rating constraints. Equation (16) is a SOC constraint. $\overline{S_{ijk}}$ is the thermal rating of the line (i,j) depending on the level l of reinforcement.

$$\tau_{ij}=\sum_{l\in\mathcal{L}}\lambda_{ijl}\overline{S}_l \quad \forall (i,j)\in\mathcal{E} \tag{15}$$

$$p_{ijt}^2+q_{ijt}^2\le\tau_{ij}^2 \quad \forall (i,j)\in\mathcal{E}, t\in\mathcal{T} \tag{16}$$

This model is computationally intractable in its Mixed Integer Second Order Cone (MISOC) form. We thus apply the Ben-Tal Nemirovski (BTN) relaxation [31] to the SOC constraints (Eqs. (8) and (16)). It consists in replacing the second order cones by linear outer approximations in an efficient way, with arbitrary accuracy. This formulation is named MISOC BTN hereafter.

2.2 Peak shaving optimization

The literature review points out the various implementation forms of the peak shaving and the dispersion of the results which can be mainly explained (Table 1) by the:

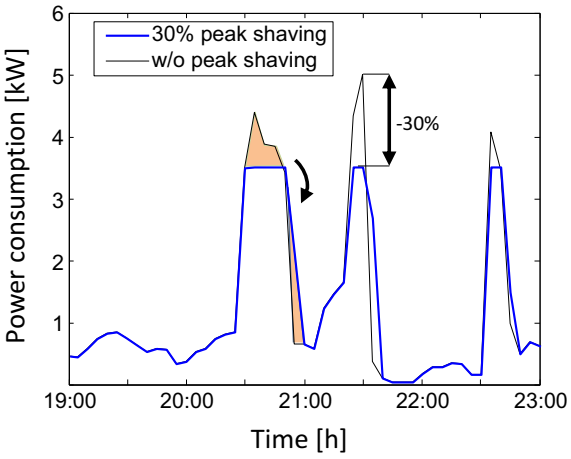


Fig. 1 Illustration of peak shaving modelling with a reduction of 30%. The energy (orange surface) is redistributed optimally on the following timesteps

– conditions: residential electrical demand, temperature, irradiation
– implemented peak shaving approach: time-differentiated tariffs or incentive payments
– available flexibilities in the distribution network

Given this, the present work implements according to [14,17,19,20], an optimal peak shaving with perfect forecasts whose the objective function is to minimize the load peak value over a given time period (Eq. 17).

$$\textbf{min}\,(max(P_t)) \tag{17}$$

The houses are equipped with the batteries, EVs and heat pumps according to the considered peak shaving capability, taken as a parameter in this study. The implemented peak shaving (Fig. 1) is characterized by:

– the peaks in load profile are cut accordingly to the peak shaving capability of the considered house.
– the peak shaved energy (orange surface, Fig. 1) is distributed optimally on the next time steps such as to ensure energy conservation.

The participating nodes of the network have different peak shaving capabilities in accordance with their contribution to the consumption peak and their current electrical flexibility.

3 Case study

This section presents the considered distribution networks, load profiles and planning parameters.

3.1 Distribution network considered

For this study, we use real data originating from a study conducted jointly by the UK DSO Electricity North West Limited (ENWL) and the university of Manchester between 2012 and 2014 that monitored 128 underground LV distribution networks to assess the impact of Low Carbon Technologies such as PV generation and heat pumps [32].

The 128 LV distribution networks are described in [33].[1] These different real networks supply between 2 and 302 customers.

3.2 Load profiles

The considered dataset includes 100 residential consumption profiles with a 5-min resolution for a winter and a summer day. These profiles have been generated with a bottom-up approach accounting for the variation of the following parameters: number of inhabitants per household, electrical appliances in use and time of use.

In this study, we want to determine the network reinforcements needed to cope with a load growth simulated over 20 years. The electricity consumption growth is determined using forecasts originating from [1] in which the total domestic electricity consumption in the UK is foreseen to increase by a rate between 29% (low scenario) and 48% (high scenario) for the period 2010–2030. This represents an annual growth rate between 1.3 and 2%.

This work models this yearly growth rate with a Gaussian distribution characterized by (μ, σ). It is parametrized such as $[\mu - 3\sigma; \mu + 3\sigma] = [1.3\%; 2\%]$. A different yearly consumption growth rate is then considered for every house by sampling this Gaussian distribution and by applying these growth rates to initial load profiles.

3.3 Planning parameters

The various parameters used in this study are listed hereunder

- **Reinforcement**: the L parameter is set to 2, i.e. we only consider one reinforcement possibility per line to limit the computational burden. Simulations on the given dataset have shown that the apparent power flow on a line at the end of the reinforcement planning horizon (year 20) could be up to three times larger than the thermal rating of this line at the beginning of the planning horizon (year 0). Hence, the reinforcement decision corresponds to tripling the capacity of this line, either by placing extra conductors in parallel of the existing one or by replacing it by a new one. This means that both line resistance and reactance are divided by three while the thermal rating of this line section is multiplied by three.
- **Cost of lines**: this study focuses on residential distribution networks characterized by underground lines. For such networks, the cost of excavation and

[1] This document and all the related network data (load profiles, network connectivity and line data) are publicly available at https://www.researchgate.net/publication/283569482_Dissemination_Document_Low_Voltage_Networks_Models_and_Low_Carbon_Technology_Profiles.

roadway/footpath reinstatement largely dominates the cost of conductors.[2] We thus make the hypothesis that the cost of reinforcement only depends on the length of the line section. It is fixed to 90 (£/km) in accordance with [34].

– **Bus voltage**: all bus voltages are restricted to the range [95%V_n;105%V_n], V_n being the 230 V nominal voltage.

3.4 Comparison metrics

We investigate the interest of peak shaving as a planning alternative following two different metrics.

1. The **competitive cost** of a peak shaving system for the different flexibility levels: 10, 20, and 30%. We consider that all network customers are equipped with peak shaving capability, so called Energy Management System (EMS), to reach the various levels of flexibility considered in this study. The competitive cost [£/unit] is defined as the maximum cost that a EMS unit can cost to compete with other planning alternatives. In the frame of this work, this competitive costs are calculated by comparing the optimal reinforcement costs with the initial load profiles (0% peak shaving) and with the shaved profiles according to the considered installed flexibility (Table 2). If there is no difference, this means that the EMS cannot compete against the other alternatives. If there is a positive difference, this means that the peak shaving saves reinforcement costs. Based on this saved reinforcement cost, the competitive cost per EMS unit is calculated.
2. The **proportion of line reinforcements avoided** for the different flexibility levels. This metric is based on the number of lines where the installed flexibility avoided reinforcement costs.

Finally, we introduce a new index, the Maximum Initial Line Loading (MILL) that will be used for the interpretation of the results presented in the next section. It corresponds to the maximal loading (in %) observed on all line sections of the given network at year 0, before load growth and reinforcements (Eq. 18). $\sqrt{p_{ijt}^2 + q_{ijt}^2}$ is the apparent power on line (i, j) at time t and $\overline{S}_1$ is the initial thermal rating of this line. Note that MILL is the worst Initial Line Loading (ILL) value of a given network and that other lines of the same network could have an ILL in an acceptable range, i.e. under its thermal rating.

$$MILL = \max_{(i,j)\in\mathcal{E}} \overbrace{\left(\frac{\sqrt{p_{ijt}^2 + q_{ijt}^2}}{\overline{S}_1} \right)}^{\text{ILL}} \tag{18}$$

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Table 2 Total cost savings achieved through the use of flexibility for the different considered networks, under various flexibility level scenarios

Network	Cost savings [£] for various flexibility levels		
	10%	20%	30%
1	0	0	0
2	15,730	67,720	88,790
3	7710	7710	7710
4	0	0	0
5	7870	67,890	67,890
6	13,560	83,650	377,680
7	29,310	43,480	152,940
8	0	53,010	65,720
9	8880	29,270	29,270
10	11,160	82,780	177,210
11	2700	41,580	41,580
12	0	0	0

4 Results analysis and discussion

4.1 Computational setup

The MILP planning model is solved with CPLEX 12.7 using the automatic Benders decomposition tool. First, we determine the networks needing reinforcement by running a power flow simulation for each network considering the initial size of lines (year 0) and the final consumption profiles (year 20). If a feasible solution is found, it means that the current size of the network lines is able to cope with load growth without any reinforcement. Otherwise, reinforcements are needed.
Among the 128 networks, 26 are identified as necessitating a reinforcement. We select 12 of these 26 networks for the rest of this study.

4.2 Competitive cost of peak shaving system

We first investigate the total cost savings achieved with different flexibility levels for the 12 considered networks. These are shown in Table 2. It can be observed that the cost savings increase with the flexibility level, which is an expected result. However, flexibility does not allow to reduce reinforcement costs for networks 1, 4, and 12. We can also observe that the cost savings widely vary between the different networks. Significant cost savings are observed for networks 6, 7, and 10 at a 30% flexibility level.

To better understand these results, we propose to calculate the MILL index introduced in the previous section. The competitive cost of peak shaving system is plotted on Fig. 2 for the 12 different networks and the different flexibility levels according to the MILL of the considered network.
We may distinguish three different zones on this graph.

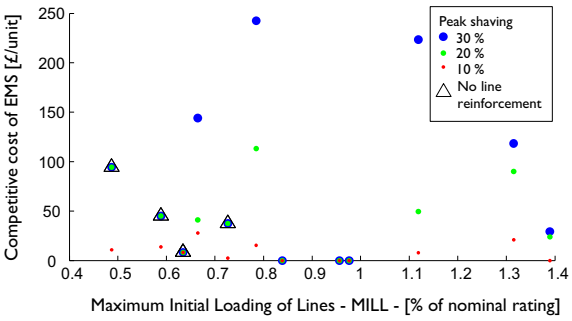


Fig. 2 Competitive cost of EMS for 12 different grid topologies and flexibility levels. The black triangle indicates the cases where the use of flexibility allows to avoid all reinforcements

$MILL \leq 80\%$

In this first zone, we can observe that the EMS competitive cost generally tends to increase with the MILL of the network. This can be explained by the fact that networks with low MILL values are likely to have less overloaded lines requiring reinforcements after the load growth. For these networks, the reinforcement costs will thus be smaller in any case, decreasing the EMS competitive costs.

We can also notice that the competitive cost of an EMS is growing with the level of the flexibility. This result is expected as the peak power on the different lines tends to decrease with higher flexibility levels.

Finally, we can see that the use of flexibility allows to completely avoid line reinforcement in 4 networks for 20 and 30% levels and in one network for a 10% level (triangle on Fig. 2).

$80\ \% \leq MILL \leq 100\%$

In this second zone of the graph, we can observe that flexibility is not competitive and does not allow to avoid reinforcements. This means that the cost savings are equal to zero with flexibility. As the most loaded lines of the network are already close to their limit (they are operated between 80 and 100% of their thermal rating), the load growth would cause the apparent power on these sections to reach loading levels far beyond 100% of their initial thermal rating. Hence, even a flexibility level of 30% could not decrease the loading of such sections below 100% of their initial rating. Reinforcement would thus be needed regardless of the flexibility level. These results are confirmed by Fig. 3, where it can be observed that lines with Initial Loading (ILL) over 72% generally need to be reinforced.

$100\% \leq MILL$

In this last part of the graph, we see that the MILL is beyond 100%. This implies that some line sections are already overloaded at year 0. Hence, they necessitate investments from the very start of the planning horizon in order to accommodate apparent power larger than the maximum power rating. In this range of MILL, we observe that flexibility allows to avoid reinforcements but that the competitive cost of an EMS is decreasing with the MILL value.

This decrease in the EMS competitive cost can be explained by two factors:

– networks characterized by MILL values above 100% at the beginning of the planning horizon have some lines already necessitating reinforcement before the load

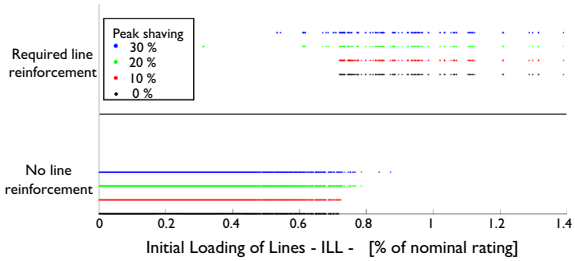


Fig. 3 Required line reinforcement for different initial load loading under different peak shaving capabilities

Table 3 Impact of peak shaving on the line reinforcement

Peak shaving capability	10%	20%	30%
Avoid investment in lines (% of lines)	3.06	13.27	19.39
Add investment (% of lines)	0	0.0	0.08

growth. For such overloaded lines, it requires reinforcement in any case because the flexibility is not able to mitigate it.

– as stated before, MILL is the worst initial line loading (ILL) value of a given network but is not representative of all the lines. In spite of a high MILL, some lines are not overloaded at the beginning of the planning study, but will become so after load growth. Depending on their load growth, this line will require a reinforcement, in the worst case. A network with a MILL above but close to 100% is more likely to have more lines slightly overloaded after the load growth than networks with a very large MILL. In such a case, flexibility can thus mitigate these lines and brings more cost savings. This explains the decrease of the EMS competitive costs for large MILL.

4.3 Proportion of line reinforcements avoided with flexibility

In the previous section, we investigated how flexibility could avoid network investments for the different considered networks considering their MILL value. We now want to look how flexibility can avoid to reinforce a particular line depending on its initial line loading (ILL), regardless of the feeder or the network. We thus present the optimal planning decisions obtained for each lines constituting the 12 considered networks. The results are presented on Fig. 3.

We first observe that there is a clear ILL limit beyond which reinforcement is needed for all lines when flexibility is not considered (Fig. 3, black dots). This limit corresponds to an ILL value of 71.8%. Then, we can also see that the use of flexibility allows to avoid reinforcing some of the lines with an ILL larger than 71.8%. However, it also implies that some lines with lower ILL values—that do not require any reinforcement when no flexibility is considered—should now be reinforced. This is due to the fact that flexibility changes the power flow pattern and might increase the loading of some line sections compared to the case without flexibility.

We show in Table 3 the proportion of lines for which investments are avoided or added compared to the case without flexibility, depending on the flexibility levels. We see that the proportion of lines for which the use of flexibility triggers investments that are not necessary without flexibility, is negligible (0.08%). However, we observe that an increasing level of flexibility helps to avoid an increasing proportion of line reinforcements, up to 20% for a 30% flexibility level.

4.4 Study limitations and research perspectives

The results presented in this work study the interest of peak shaving system as a planning alternative. This study embeds some limitations which could impact the presented results:

- The optimal peak shaving is implemented with perfect forecast. The results obtained in this study should thus be considered as upper bounds on the real economical interest of peak shaving as a planning alternative.
- The planning method considers a balanced grid. The results might be influenced by the inherent unbalance of LV networks. This necessitates further investigations. As a matter of fact, a peak shaving approach that would not consider the different phases of the network could worsen then unbalance, hence reducing the positive impact of peak shaving.
- The results presented are valid only for the considered grid topology under a yearly growth rate of the electrical demand between 1.3 and 2%. However, they show that there is a clear ILL limit that can be identified above which reinforcements are needed. Future work could investigate how this ILL limit varies with the foreseen load growth.

5 Conclusion

The foreseen increase of residential electricity consumption will force the Distribution System Operators to reinforce their networks at great expense, to cope with larger power flows. Nevertheless, the flexible nature of future installed electrical devices makes the problem part of the solution because it allows the house to become an active part of the grid using their flexibilities, e.g. batteries, EVs or heat pumps, for peak shaving.

This paper paves the way for considering peak shaving as a planning alternative for distribution network reinforcement by i) formulating this problem according to state-of-the-art planning and peak shaving methods and by ii) quantifying its potential costs to compete with line reinforcements. For this purpose, a Convex DistFlow-based planning model proven to be exact or close to exact in numerous practical cases is combined with an optimal peak shaving approach.

In this 20-year planning study, 12 real UK networks, their associated load profiles and three different peak shaving levels: 10, 20, and 30%, are studied. The results are compared according to two metrics: the competitive cost of residential EMS allowing to perform peak shaving and the proportion of line reinforcements avoided for the

different peak shaving levels, in view of the Maximum Initial Line Loading (MILL) measured on each network.

This paper answers to two fundamental questions:

Is it possible to identify a decision planning metric which determines if reinforcement is needed for a particular line? How is it impacted by the use of flexibility?

The MILL metric, based on information available at the beginning of the planning horizon, seems to be an appropriated indicator for reinforcement decision. This study highlights that (i) a peak shaving level of 20 or 30% can avoid all line reinforcement for networks characterized by MILL under 80%; (ii) peak shaving is not competitive for networks characterized by a MILL between 80 and 100%, i.e. when the network is already operated close to its limits; (iii) peak shaving is a cost-efficient planning alternative for networks initially overloaded, i.e. with a MILL over 100% and avoid part of the reinforcements that would otherwise be needed. In addition, this study points out that all lines with an initial loading (ILL) over 72% require a reinforcement in a context without flexibility. Nonetheless, a 30% level of peak shaving allows to avoid reinforcements for 20 % of the aforementioned lines.

What would be the maximum EMS cost to compete with line reinforcement?

Results highlight that EMS can be economically competitive with network reinforcements if its cost is between 10 and 250 £/unit for networks with a MILL under 80%, leading to savings between 3000 and 370,000£, depending on the considered network.

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