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On the impact of energy caps on the costs of cellular networks with different layouts and technologies

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Abstract: In this paper we investigate the options of a network operator faced with the requirement of reducing its carbon footprint, expressed in terms of a global energy cap. First, we propose two ways to meet the energy limitations: by efficiently managing the energy consumed by the legacy networks or by installing additional capacity to the initial topology. We show the power savings that can be obtained in both cases as well as the incurred costs. Then, we identify the initial composition of the network and the available technology in the upgrade phase as the factors that have the most influence on the ability of a network to meet the energy caps. Finally, we show the intrinsic unfairness of the energy caps, which are imposed to all the networks without taking into account the differences among them. Therefore, we highlight the fundamental role of carbon markets and emission trading systems in guaranteeing a measure of fairness between the operators.

Key Words: Energy caps, cellular networks, carbon markets, carbon footprint, energy management.

1 Introduction

According to the National Oceanic and Atmospheric Administration,[1] 2014 was the warmest year globally since measurements began in 1880. In particular, the ten warmest years in the 135-years of recorded values have all occurred since 1998, a sign of the relentless world-wide warming that poses severe long-term risks to civilization and to the natural world [14]. Despite the public debate surrounding global warming, the natural greenhouse effect is well accepted in the scientific community. Without the heat-blocking action of clouds, water vapor and greenhouse gases (GHGs), the Earth climate would be about 33°C cooler than it is [16].

While natural causes are surely responsible for some part of the climate change, they cannot explain by themselves some recent and more striking changes. For instance, since the mid-twentieth century, the Earth's average temperature has increased from 14°C to 14.5°C, the sea level has risen about 10 centimeters and the snow cover of the Northern hemisphere has shrunk by 2 million square kilometers [11]. Other impacts involve more intense rainfalls, more frequent and extreme heat waves, the increase in wildfires and ocean acidification. Solid research work, conducted by different organizations and using different methodology, suggests that this is largely caused by human activities, especially the release of carbon dioxide (CO_2) and other greenhouse gases, from burning fossil fuels, which are abundant and therefore cheap [15].

We must reduce our carbon footprint using different policies, such as taxes, pricing or, as is often proposed, by imposing a global cap on carbon emission for an industrial sector or even a whole economy. Energy caps will be set for the information and communication technology (ICT) sector just as any other, since ICT makes up a small but not insignificant part of greenhouse gas emissions: about 2% of global CO_2 emissions and about 1.5% of global CO_2 equivalent (CO_2e) emissions in 2007 [17]. [2] Moreover, while the SMART2020 report predicted that the overall ICT footprint will not quite double by 2020, according to [8], the footprint of mobile communications alone could almost triple within the same time period. To get a sense of the speed at which wireless communications are expanding, consider that 15 years after the first phone call using Global System for Mobile Communications (GSM) occurred in 1991, the number of GSM users was over 2 billion. Today, the total number of mobile subscriptions in the world has reached nearly 7.5 billion, or about 95.5% of the world population. For these reasons, there is a strong incentive to reduce the energy consumption of wireless communications.

Exhaustive reviews of green mobile challenges can be found in [7, 18, 9, 6]. One technique that looks particularly promising is the concept of energy-aware management of existing networks. Several techniques have been proposed in the literature (see for example [5, 12, 13]), all exploiting the typical space and time variations of mobile traffic. This is especially useful in cities where most subscribers will be in the core area during business hours and in the suburbs during the evening and week-ends. One can then reduce the energy use by turning off some cells in low-use areas and using the remaining active cells to provide coverage. If needed, these active cells can increase their power to eliminate possible coverage holes left by turned-off BSs.

While energy management is a good starting point to reduce the carbon footprint of mobile networks, there is still room for improvement. In our previous work [3, 4] we have introduced the idea of jointly optimizing the network design, based on a trade-off between capital expenses (CapEx) and operational ones (OpEx), and the network operation to follow the traffic variations over time. For this, we developed a joint planning and energy management (JPEM) optimization framework. We demonstrated that, during off-peak periods, networks designed with the joint optimization can more easily adapt to traffic changes and that this higher flexibility can yield large reductions of energy cost.

In this paper, we build on our previous work in order to study how a mobile operator could respond to a requirement to reduce its carbon footprint as expressed by an overall energy cap. Considering heterogeneous networks (also referred to as HetNets) configurations, where macro and small cell technologies coexist in the same topology, our main goal is to show that costs required to operators to meet a specific energy cap are strongly dependent on the network layout and the base station technology. Deviations from costs

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[1] NOAA is a federal agency within the United States Department of Commerce focused on the conditions of the oceans and the atmosphere.

[2] CO_2e is used to express the impact of each different greenhouse gas in terms of the amount of CO_2 that would create the same amount of warming.

proportional to energy objectives are mainly due to the complex structure of network design problems that need to consider both service area coverage and capacity dimensioning. We show that our optimization tool is particularly useful to perform a quantitative analysis of these effects and to define possible fair policies of cost management. To the best of our knowledge, this is the first study of the effect of cellular network characteristics on the costs incurred to meet energy saving targets.

1. In Section 3, we try to answer the question *How can operators meet the energy caps, and how much would it cost?* We show how this can be done by managing more efficiently the energy used by legacy networks or, if this is not enough, by installing additional capacity. We highlight the energy savings that can be obtained as well as the costs that are incurred.
2. The next question is *What factors have the largest influence on the ability to meet the energy caps?* This is investigated in Section 4 where we consider different legacy networks. Each topology shows a different ability to adapt to the energy caps. We investigate the elements that are mostly responsible for these variations, we explain their impact and show how they are affected by the network topology.
3. Finally, in Section 5, we try to see *How can the authority implement the energy caps fairly for all network topologies?* Because energy caps are set for all the networks in a given area, they cannot take into account the differences among the networks. This in turn can have a large effect on the cost that an operator will have to incur to meet the caps. Thus, we consider legacy topologies with various characteristics, as well as different technology scenarios and show why carbon markets are necessary to guarantee a measure of fairness between the operators.

2 Assumptions and model

We can answer these questions using the joint planning and energy management (JPEM) model presented in [3]. First, we describe the various assumptions we have considered for the base stations and traffic and the scenarios that we used. Finally, we recall the original JPEM formulation which serves as the basis for specific models used to answer the questions.

2.1 Base station parameters

We consider three kinds of LTE base stations (BSs) with features displayed in Table 1. Configuration $C1$ is an example of macro BS with large traffic capacity and power. These are typical of what is currently used in mobile networks. Configurations $C2$ and $C3$ are micro and pico BSs that have lower cost and power requirements but a somewhat lower capacity. We assumed that a network operator already owns the right to deploy some access stations in locations called *candidate sites* (CSs) so that the "cost" column is simply the price of the device. The heading "power" represents the total power needed by the BS, including power amplifier, signal generator, cooling system and microwave link. This is the amount of power used whenever the station is turned on. Power and capacity values, extracted from [2], are the same used by GreenTouch, a large consortium of more than fifty institutions including manufacturers and operators, dedicated to significantly reduce the carbon footprint of ICT networks, devices and platforms (`http://www.greentouch.org/`). Finally, we assume an energy cost of 0.2 € per kWh and the network lifetime to be about 14 years. We also present in Table 2 some information used to compute the a_{ijk} matrix described in Table 5. The actual power used for transmitting the data is shown in column "transmitted power" and the coverage radius in the last column was calculated by using the Cost-231 Hata model for suburban scenarios [10].

Table 1: Base station parameters

Configuration	Cost (€)	Power (W)	Capacity (Mb/s)
$C1$	30000	1350	210
$C2$	10000	144.6	70
$C3$	1000	14.7	70

Table 2: Parameters for coverage radius

Configuration	Transmitted Power (W)	Coverage Radius (m)
$C1$	19.9	1230
$C2$	6.3	850
$C3$	0.1	241

Table 3: Traffic profile

Index	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
Start	00:00	2:00	4:00	8:00	10:00	13:00	18:00	20:00
End	2:00	4:00	8:00	10:00	13:00	18:00	20:00	24:00
Length (h)	2	2	4	2	3	5	2	4
ρ_t	0.8	0.55	0.25	0.45	0.65	0.8	0.9	1

2.2 Traffic variations

We model the variations of the traffic in the service area using a daily traffic profile. The values for a suburban area, based on downlink traffic measurements [1], is shown in Table 3, which displays the start and end time of each period, its length as well as the fraction ρ_t of the traffic load in the busiest period. The traffic enters the network through a set of *traffic test points* (TPs), representing traffic aggregation centers which are uniformly spread in the area. For every time interval we assign to each traffic test point a uniform random value $20 \leq \tau \leq 40 Mb/s$, together with a random number $0 \leq \alpha \leq 1$. The traffic generated at the test point is τ if $\alpha \leq \rho_t$. Otherwise, it is set to 0. We also introduce *coverage test points* that do not produce any traffic. They are set on a regular grid overlaying the area to ensure complete coverage in the off-traffic regions when dimensioning.

2.3 Test scenarios

Using the base station parameters and the traffic profile described above, we define six test scenarios reported in Table 4. They are ordered from the smallest to the largest in terms of number of CSs and traffic TPs. The name of each scenario indicates the number of candidate sites and traffic test points in the form of $S\_\#CSs\_\#TPs$. The second entry represents the measure of the side of the square service area, while the second one is the number of candidate sites randomly located in the area and initially available to the operator. Next, the numbers of traffic and coverage test points are shown in the last two columns.

The mathematical model was implemented using the AMPL modeling language and optimized with the CPLEX solver. For each scenario, we set the solver to stop when the optimality gap became smaller than 2% or after 2 hours 30 minutes of computation. However, for the largest scenarios, we were forced to run the instances for several hours to reach optimality gaps lower than 20%.

2.4 The basic optimization model

We now recall the joint planning and energy management (JPEM) framework first proposed in [3] to provide the reader with a detailed insight into the trade-off that we want to study. The JPEM framework finds jointly

Table 4: Scenario parameters

Scenario	Area (km)	CSs	Traffic TPs	Coverage TPs
S_60_30	2×2	60	30	121
S_100_50	3×3	100	50	256
S_120_60	4×4	120	60	441
S_180_80	5×5	180	80	676
S_220_100	4×4	220	100	441
S_250_120	6×6	250	120	961

Table 5: JPEM parameters and variables

Parameters	**Description**
I_c	Set of coverage TPs
I_t	Set of traffic TPs
S	Set of candidate sites to locate BSs
K_j	Set of possible configurations for a BS located in $j \in S$
T	Set of time intervals
δ_t	Length of time period $t \in T$
p_{it}	Traffic provided by the TP $i \in I_t$ in period $t \in T$
c_{jk}	Capacity of the BS located in $j \in S$ with configuration $k \in K_j$
γ_{jk}	Cost for a BS located in $j \in S$ with configuration $k \in K_j$
ϵ_{jk}	Power rating for a BS located in $j \in S$ with configuration $k \in K_j$
β	Weight parameter used to trade-off the objective function
φ	Factor to actualize the daily energy cost for the network lifetime
a_{ijk}	Binary, equal to 1 if TP $i \in I_c \cup I_t$ is covered by a BS installed in $j \in S$ with configuration $k \in K_j$
Variables	**Description**
z_{jk}	Binary, equal to 1 if a BS is installed in $j \in S$ with configuration $k \in K_j$
y_{jkt}	Binary, equal to 1 if a BS installed in $j \in S$ with configuration $k \in K_j$ is active in period $t \in T$
x_{ijt}	Binary, equal to 1 if TP $i \in I_t$ is assigned to a BS located in $j \in S$ in period $t \in T$

the optimal base station locations, capacity and scheduling following a traffic demand pattern. This is a two-criteria optimization where the two objectives are capital and operation costs over some network lifetime. The JPEM model minimizes a trade-off between these two objectives while meeting coverage constraints.

The parameters and variables used in the model are defined in Table 5. The JPEM optimization model is:

$$\min \quad (1-\beta)\sum_{j \in S}\sum_{k \in K_j} z_{jk}\gamma_{jk} + \beta\varphi\sum_{j \in S}\sum_{k \in K_j}\sum_{t \in T}\epsilon_{jk}\delta_t y_{jkt} \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in S}\sum_{k \in K_j} a_{ijk}y_{jkt} \geq 1 \quad \forall i \in I_c \cup I_t, t \in T \tag{2}$$

$$x_{ijt} \leq \sum_{k \in K_j} a_{ijk}y_{jkt} \quad \forall i \in I_t, j \in S, t \in T \tag{3}$$

$$\sum_{j \in S} x_{ijt} = 1 \quad \forall i \in I_t, t \in T \tag{4}$$

$$\sum_{i \in I_t} x_{ijt}p_{it} \leq \sum_{k \in K_j} c_{jk}y_{jkt} \quad \forall j \in S, t \in T \tag{5}$$

$$y_{jkt} \leq z_{jk} \quad \forall j \in S, k \in K_j, t \in T \tag{6}$$

$$\sum_{k \in K_j} z_{jk} \leq 1 \quad \forall j \in S \tag{7}$$

$$z_{jk}, y_{jkt}, x_{ijt} \in \{0,1\} \quad \forall i \in I_t, j \in S, k \in K_j, t \in T \tag{8}$$

The objective function (1) is a convex combination of a CapEx term, which accounts for the cost of the BSs, and an OpEx term, which is the total cost of the energy used over all time periods when base stations are turned on. This is amortized by a coefficient φ to make it compatible with the capital cost of the BSs. The weight parameter β is used to tune the trade-off between the two components of the objective function.

There are three sets of decision variables. The variables z are used to choose the BSs installed on the various CSs, the y are the scheduling variables to determine when a BS will be turned on or off and the z variables assign the TPs to the BSs.

The first set of *global coverage constraints* (2) guarantee that all TPs lay in the coverage radius of at least one switched-on BSs. In addition, *traffic TP coverage constraints* (3) insure that every traffic TP is assigned to an active BS that covers it. *Assignment constraints* (4) impose that every traffic TP is assigned to exactly one BS in each time period. Idle TPs that are not requesting traffic in a certain time interval are also assigned to a BS, but they do not contribute any traffic to the BS load. *Capacity constraints* (5) guarantee that each BS has enough capacity to satisfy the assigned traffic in every time period. *Activation constraints* (6) state that an access device can be switched on only if the device is actually installed in that location. Every candidate site can host at most one type of access station, as specified by *configuration constraints* (7). Finally, *domain constraints* (8) assert that all the three groups of variables are binary.

3 Meeting energy caps: How and at what price?

Network operators can meet energy caps in one of two ways: 1) implement energy management on their legacy network or, if this is not enough, 2) add some more base stations. Having more base stations gives more flexibility to perform a better energy management. In this section, we try to quantify the costs and potential savings of each option. In order to do this, we need to explain how legacy networks are built in the first place.

3.1 Legacy network design

We assume that current networks are designed to minimize the total capital expense subject to some coverage constraints with no consideration for energy savings. We also assume that only large base stations of type $C1$ are currently available. This is not unreasonable since small base stations are only starting to be used. We also assume that the technology for energy management is present in the base stations but is not currently used. Based on these assumptions, we design the legacy networks using the JPEM model with the following modifications:

- All time dependence is removed from the constraints and variables.
- All installed base stations are always on so that the activation variables y_{jkt} are replaced by installation variables z_{jk} in constraints (2), (3) and (5).
- Similarly, the assignment does not depend on time so that the x_{ijt} are replaced by x_{ij}.
- We drop the activation constraints (6) since the BS are always on.
- We design the network to minimize only capital cost. Operation costs are dropped and we set $\beta = 0$ in (1).
- We need coverage under all traffic conditions so that we replace p_{it} in constraints (5) by $\hat{p}_i = \max_t p_{it}$.

We define the resulting network CapEx as:

$$C_0^c = \sum_{j \in S} \sum_{k \in K_j} z_{jk} \gamma_{jk}$$

and the corresponding operation cost C_0^e is given by

$$C_0^e = \varphi \sum_{j \in S} \sum_{k \in K_j} \epsilon_{jk} z_{jk}.$$

Both C_0^c and C_0^e are used as reference values in what follows.

3.2 Zero-cost solution: Legacy network operation management

We assumed that the legacy networks have energy management technology so that the easiest solution to meet the energy caps is to enable them. The objective is to achieve the maximum power savings allowed by the legacy topology. If this is enough, the operator can meet the caps without any extra expense. For this, the basic framework described in Section 2.4 is modified as follows:

- Only operation costs have to be minimized and we set $\beta = 1$ in (1) to get the objective:

$$C_s^e = \varphi \sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jk} \delta_t y_{jkt}.$$

- To account for the devices already in place, we define a new set of binary parameters $\tau_{jk} = 1$ if a base station is installed in site j with configuration k and $\tau_{jk} = 0$ otherwise. The τ_{jk} replace z_{jk} in constraints (6).
- No additional device can be installed, so constraints (7) are dropped.

For every tested scenario, we show in Table 6 the energy savings when energy management is used in the legacy network. The percentages are computed as $100 \times ((C_s^e - C_0^e)/C_0^e)$. Depending on the initial configuration, we can see from these results that the savings can be quite large in some cases. The reason is that legacy topologies only use macro cells which must serve the maximum amount of traffic during the day in every test point location. This will require a lot of power that has to be turned on all the time so that one can expect that turning these large BSs off during off-peak periods will produce large savings. We see that we can save as much as 42% with no extra CapEx for scenario S_220_100, but less than 10% for scenario S_180_80. Results between 25% and 40% were obtained for the other four scenarios, measuring an average of about 26% OpEx reduction overall.

Table 6: Zero-cost energy reduction: Energy savings with cell sleeping in legacy topology

Scenario	Energy Savings (%)
S_60_30	−34.72
S_100_50	−40.42
S_120_60	−31.25
S_180_80	−9.64
S_220_100	−41.88
S_250_120	−26.56

The fact that older networks might meet energy caps at little, if no extra cost, just by using energy management on their older technology and less efficient cells is certainly good news. On the other hand, we see that this is not so easy for some other legacy networks. This has important consequences for energy cap policies that are discussed in Section 5.

3.3 Legacy network upgrade

If the operator cannot meet the energy caps by managing the base stations in the legacy network, more BSs have to be added. With additional access stations present, it is possible to turn off more BSs during low traffic periods and reduce energy. The question is whether these savings can offset the added BSs' cost.

Operator can limit new CapEx expenses by installing new base stations on the candidate sites that we assumed it already owns and that are not currently used. We assume that an operator wants to minimize the total cost of the upgrade, i.e., additional capital costs and total operation expenses. We also assume that an energy management mechanism is used on all BSs, both legacy and newly deployed. Once again, we modify the JPEM formulation in Section 2.4 to compute the upgraded networks.

- The legacy BSs cannot be removed or changed, but only managed.
- We define S' as the set of sites j occupied by legacy BSs, and K'_j as the corresponding set of configurations. We set
$$z_{jk} = 1 \quad \forall j \in S', k \in K'_j.$$
- The operator wants to minimize the total actualized cost of the upgrade so that the objective function (1) is modified to give the same weight to both additional CapEx and total OpEx terms:

$$\begin{aligned} C_u &= C_u^c + C_u^e \\ &= \sum_{j \in S/S'} \sum_{k \in K_j} z_{jk}\gamma_{jk} + \varphi \sum_{j \in S} \sum_{k \in K_j} \sum_{t \in T} \epsilon_{jk}\delta_t y_{jkt}. \end{aligned}$$

- A new constraint is introduced to model the power cap. The energy use of the upgraded network is reduced by $100 - P$ percent with respect to C_0^e:

$$\sum_{j\in S}\sum_{k\in K_j}\sum_{t\in T}\epsilon_{jk}h(t)y_{jkt} \le PC_0^e.$$

If a feasible solution is found, the operator can meet the cap by upgrading its network topology using only the candidate sites available at that moment. If not, new candidate sites must be rented and more BSs must be installed.

Consider first the case where only macro cells can be used to upgrade the legacy topologies. In Table 7 we gather the maximum energy savings that can be achieved by installing $C1$ base stations over the test scenarios' initial topologies. We explain the table entries using S_60_30. We know from Table 6 that we can meet a cap of 34.7% just by energy management. Any further reduction must be met by installing more BSs. The question is then how far we can go and at what cost until this is no longer possible. To do this, we solve a sequence of problems with decreasing values of P until we cannot get a feasible solution. The first value we try is $P = 65\%$. For this, we get two values for the Opex reduction.

$$\Delta C_{u,0}^e = \frac{C_u^e - C_0^e}{C_0^e}$$
$$\Delta C_{u,s}^e = \frac{C_u^e - C_s^e}{C_s^s}$$

In the first case, we measure with respect to the energy cost of the unmanaged legacy topology and in the second, with the managed topology. Because the energy requirement is lower than what can be obtained with management only, there will be an additional CapEx:

$$\Delta C_{u,0}^c = \frac{C_u^c - C_0^c}{C_0^c}.$$

With $P = 65\%$, we get:

$$\Delta C_{u,0}^e = -38.89\%$$
$$\Delta C_{u,s}^e = -6.38\%$$
$$\Delta C_{u,0}^c = +16.67\%$$

Note that the energy is lower than the requirement because we can only add an integer number of BS. In the present case, the solution with $P = 65\%$ has one more BS than the initial solution but this is enough to lower the energy to 61% of the original, even though the constraint requires only a reduction to 65%.

Table 7: Maximum energy savings with $C1$

Scenario	$\Delta C_{u,0}^e$ (%)	$\Delta C_{u,s}^e$ (%)	$\Delta C_{u,0}^c$ (%)
S_60_30	−38.89	−6.38	+16.67
S_100_50	–	–	–
S_120_60	−37.50	−9.10	+8.34
S_180_80	−30.47	−23.05	+50.00
S_220_100	−45.21	−5.73	+15.00
S_250_120	−30.38	−5.20	+4.17

Next, we try $P = 60\%$ and find that it is not possible to meet the constraint using only the current candidate sites. The results are summarized in the table which shows the smallest values of $\Delta C_{u,0}^e$, $\Delta C_{u,s}^e$ and $\Delta C_{u,0}^c$ for all scenarios.

In case of scenario S_100_50, it is simply not possible to reduce the energy consumption below C_s^e by adding new macro base stations on the current CSs. Meeting the cap would require renting new sites to install more base stations.

Scenario S_180_80 shows the opposite situation where one can reduce the energy by about 23% below C_s^e with the current CSs. As we saw in Table 6, energy management can reduce the energy only by 9.64% from the original C_0^e, by far the lowest value among the set of results. Adding more $C1$ base stations provides just enough flexibility to enable the large savings from the upgrade. On the other hand, such energy efficiency improvement comes at the price of a large additional capital investments of 50% the initial CapEx C_0^c.

For the other scenarios, on the average, we get modest savings of 5.28% of C_s^e, with an average extra installation cost of 8.84% of the original CapEx C_0^c.

3.4 Summary

These results show that meeting a fixed energy cap could be a very different task for different operators if the only option is to use large BSs on the current CSs. We have seen that it is often, but not always, easy to meet large reductions when the original network is not managed. Still, we notice that energy cuts equal or greater than 40% to 45% of the initial OpEx C_0^e are out of reach with a $C1$-only topology upgrade. Meeting energy caps is often much harder for a network that already uses energy management. It may simply be impossible, or require large capital costs. Also, in most cases, only modest improvements of around 5–10% are possible.

One of the main reasons to the differences in the network behaviors is the impact of coverage constraints (2) and (3). If mainly driven by the capacity constraints (5), the network layout is provided with a higher level of flexibility, while if the coverage component prevails, the topology might not have enough room to allow significant energy savings. In the next section, we try to get more insight on the possible causes and consider the impact of using BSs with different kinds of cost-energy tradeoffs.

4 What impacts the ability to meet energy caps?

Intuitively, every topology would respond differently to enforced energy limitations. While we cannot exactly predict each network behavior, we are able to identify the major aspects that influence the ability of access networks to comply with energy caps.

4.1 Composition of the legacy networks

In Section 3.2, we assumed that both legacy and upgraded networks used only large base stations of type $C1$ such as the ones currently in use. This is somewhat restrictive since future base stations will most likely be much smaller, with lower energy use, smaller coverage and hence smaller cell size. Here we want to estimate the effect of using base stations of types $C2$ and $C3$ when trying to meet energy caps. This can have an impact either because they are already implemented in the legacy network, or as an upgrade path from a standard, large-BS legacy network.

First, we assume that the legacy networks was built using both $C2$ and $C3$ base stations in addition to $C1$. This would be the case for a network operator that recently deployed or remodeled its cellular network. The first effect would be on the cost of the legacy network itself and also on the efficiency of energy management as a tool to meet the caps. Some interesting outcomes are shown in Table 8 where we have two blocks of results, one where the legacy topology uses only macro cells $C1$ and the other where both micro and pico cells $C2$ and $C3$ are used in addition to $C1$. In each block, we show for every scenario the OpEx C_0^e of the unmanaged legacy networks and C_s^e when energy management is used. We also show the percent cost reduction achieved by energy management:

$$\Delta C_l^e = \frac{C_s^e - C_0^e}{C_0^e}.$$

The most striking result is the large difference in both CapEx and OpEx between networks using only $C1$ cells and the ones with the $C2$ and $C3$ cells. With smaller cell sizes, a minimum-CapEx topology can focus the coverage capabilities in those areas where the highest traffic is offered. The initial operation and capital

Table 8: Outcome of cell sleeping mechanism on different legacy configurations

	Legacy: $C1$			Legacy: $C1, C2, C3$		
	C_0^e	C_s^e	ΔC_l^e (%)	C_0^e	C_s^e	ΔC_l^e (%)
S_60_30	194 400	126 900	−34.72	23 054	16 895	−26.72
S_100_50	324 000	193 050	−40.42	115 783	103 493	−10.62
S_120_60	388 800	267 300	−31.25	151 358	143 082	−5.47
S_180_80	518 400	468 450	−9.64	177 120	164 728	−7.00
S_220_100	648 000	376 650	−41.88	113 198	96 543	−14.70
S_250_120	777 600	571 050	−26.56	258 034	239 585	−7.15

costs are much lower with respect to the macro cell legacy network values. This higher network efficiency, on the other hand, means that turning on the cell sleeping mechanism will yield much lower savings than when the legacy network is $C1$-only. The multiple-cell legacy network is much energy-efficient in the first place so that simply turning on the energy management with the same set of cells is not going to gain much.

This makes an important difference when the same energy caps are set for many operators at the same time. Operators owning small-cell networks were able to save a considerable amount of energy and money before the caps but they may be forced to resort to a network upgrade to meet them when they are imposed, with the corresponding large capital investment. Large-cell-only operators would operate a more costly network before the caps but would be able to meet them at a much lower cost since their legacy network is not very energy-efficient in the first place. As an example, consider the energy cap of 30%. We notice that macro cell network operators would need to lay out capital to meet the cap only for the two scenarios S_180_80 and S_250_120. This is in contrast to network operators with multiple technologies, where an upgrade would be needed in all scenarios.

4.2 Network upgrade and technology availability

Upgrading a legacy network means that new equipment has to be purchased. This depends on what technology is currently available. We have seen in Section 3.3 the efficiency of energy management and upgrade costs when we assume that only $C1$ BSs are available for the upgrade. Here, we assume first that $C2$ micro cells are also available in addition to $C1$. These are less expensive and more energy efficient so that they may afford a less costly upgrade path. In the last case, the operator can choose between three types of devices, including the most recent $C3$ pico cell technology. This offers the highest connection quality and the minimum CapEx and OpEx per unit of capacity.

4.2.1 Macro and micro cell upgrade

First we examine network upgrades with a mix of macro and micro cells since these can adapt more easily to the caps. We tested several decreasing values of P, increasing the number of additional BSs depending on P up until $P = 30\%$, since we do not think that lower values would be very realistic. Note however that lower values could potentially be reached if needed. We show in Table 9 the capital investment needed to reduce the original OpEx C_0^e by at least 70% assuming that both $C1$ and $C2$ base station types are available. We see that we can meet the energy cap by spending about 45% to 55% of the initial C_0^c. The advantage in terms of adaptability is evident compared to the upgrade with macro cells only.

Table 9: Network upgrade with $C1$ and $C2$: Additional CapEx for 70% cap

Scenario	Additional CapEx (%)
S_60_30	+55.56
S_100_50	+43.33
S_120_60	+52.78
S_180_80	+54.17
S_220_100	+48.33
S_250_120	+54.17

4.2.2 Macro, micro and pico cell upgrade

The results are even more striking when pico cells are available, as can be seen from Table 10 where we show the energy savings, the additional capital investments and the types of new installed BSs. Here, the value of P is set to be slightly lower than the maximum energy savings achievable through an energy-aware management of the legacy network. This is the smallest value of P that forces an upgrade. We see that the most cost-effective solutions use highly energy-efficient topologies. No additional macro cells are deployed and a large number of extra micro and pico cells allow most of the legacy base stations to be switched off during a great part of the day, thus dramatically decreasing the energy use. The additional cost of new equipment is not negligible but this is balanced by extremely low operational cost. In other words, when the most modern technologies are within reach, it is in the operator's best interest to invest in a deep greening of its network regardless of the GHG emission caps imposed by the authorities.

Table 10: Network upgrade with $C1$, $C2$ and $C3$

Scenario	Energy Savings	Additional CapEx	New BSs		
	(%)	(%)	$C1$	$C2$	$C3$
S_60_30	-91.14	$+29.44$	0	4	13
S_100_50	-79.67	$+24.00$	0	5	22
S_120_60	-85.72	$+38.33$	0	39	0
S_180_80	-83.27	$+42.29$	0	17	33
S_220_100	-87.28	$+27.00$	0	10	62
S_250_120	-77.71	$+35.28$	0	21	44

The disadvantage of having only large cells is clear from Table 10. Micro and pico cells allow network operators in both scenarios to achieve very large power reductions at a reasonable price. Large energy caps of -40% to -50% of the initial value C_0^e, correspond to the lowest value of total costs for upgrades with $C1$ and $C2$ base stations. In these cases, the energy savings fully make up the added capital expenses. Tighter caps can be achieved only with capital investments that are large enough that they are only partially repaid by the power savings. Still, in all cases, the overall costs do not exceed 85% to 90% of the original sum of CapEx and OpEx.

5 How can energy caps be implemented fairly?

As we emphasized throughout this paper, network topologies with different characteristics show different ability to adapt to energy consumption regulations. The particular situation where operators are subjected to limited technology availability highlights the need of an intermediary entity or system, created to insure a certain level of fairness among the involved parties. In this sense, carbon markets play a primary role in the context of energy consumption regulation. Emission trading schemes (ETS) represent one of many market-based mechanisms. Once a certain cap is set on the total amount of produced GHGs, emission allowances (or credits) are distributed amongst the participating companies. Members can trade allowances with one another as needed, as well as buy a certain number of credits from emission reduction projects around the world. At prearranged times, participating companies must turn in to the authorities enough allowances to cover their GHG emissions. Companies that managed to reduce their emissions can save the extra allowances for the year to come or sell them to other companies in need. Without carbon markets, every network operator unable to reach the agreed target would incur heavy fines by the regulatory entity. Instead, emission trading schemes allow operators to compensate for their high emissions by buying carbon credits from more virtuous participants, which in turn will be rewarded with extra income for their energy reduction efforts.

In light of the previous results, it should be clear that imposing the same energy cap to a number of operators each with a different network could lead to extremely unfair situations. This can happen for a number of reasons that we discuss in Section 5.1. This points out the need to some mechanism to prevent this unfairness and we discuss in Section 5.2 how a carbon market can be used to that effect.

5.1 Unfairness

Unfairness could arise because of the structure of the legacy networks as we have seen in Section 3. Here, all networks use the same technology $C1$ and can upgrade using only this technology. In this sense, this is an equal playing field but we have seen in Table 7 that even in this case, some operators may not be able to meet the caps at all while other could meet them at a very small cost. This is simply due to the different traffic demands in each network which has led to legacy network structures that can be more or less energy-efficient. The more inefficient the original network, the easier it will be to meet the caps simply by turning energy management on or by upgrading a few more BS. For the more energy-efficient legacy networks, this will be either very costly, or not possible at all, since there is no "slack" in the first place.

Unfairness can also arise because different operators may be using different technologies in their legacy network. This is shown in Table 8 where we see that legacy networks with more advanced technology like $C2$ or $C3$ may have a very hard time meeting energy caps. This in contrast with less efficient, all-$C1$ networks where it is possible to reduce the energy at little cost. In that sense, inefficient operators are at an advantage when the caps are set up. Finally, the upgrade path that is available also has a strong effect on meeting the caps. To see this, we present some plots of the cost or energy as a function of the cap.

Consider first a network in scenario S_180_180. In Figure 1a, we show the total cost of the network, $C_0^e + C_0^c$ plus any additional CapEx, as a function of different energy caps. The leftmost point on all graphs is set at 100% and is for the reference legacy topology. The point labelled "sleep" represents the cost when using energy management on the legacy network. The following points show the relative cost due to upgrades forced by increasingly tighter caps. We also plot on Figure 1b the energy cost relative to C_0^e as the caps become tighter.

We show three possible upgrade paths. Bold lines for macro cells only, dotted lines when macro and micro cells are used while dashed lines correspond to upgrades with macro, micro and pico cells. Note that the segment from "initial" to "sleep" does not involve any network upgrade and it is the same for all three cases. The curves are plotted until either there is no feasible solution or the energy consumption has been reduced to 30% of C_0^e.

Consider the solid line where only $C1$ upgrades are available. Imagine that the energy caps are set at 75% of the original OpEx. In this case, a successful $C1$ upgrade will be fairly cheap, possible by spending an amount corresponding to the 12.5% of C_0^c. Considering the extra capital investments and the lower OpEx, the total costs decrease to about 92% the original value. If, however, the energy caps are set at -30% of C_0^e, this small extra 5% decrease is very costly. The total cost rises to about 108% the legacy value, due to additional CapEx corresponding to as much as 50% of C_0^c. Compare this with the situation of an operator in scenario S_220_100, as shown in Figures 2a for the total cost and 2b for the energy cost. The solid line shows that this operator could meet a reduction of 40% just by enable an energy management mechanism. If the cap is further reduced to 45%, the resulting total cost would still be about 84% of the legacy cost. Clearly, this operator is in a much better situation than the one in scenario S_180_180 at the time the caps are set. Other cases show similar differences depending on the efficiency of the legacy network.[3]

5.2 Market value

In all that follows, we consider that the CapEx of the legacy network is a sunk cost. The total cost of a network under some upgrade strategy is the CapEx of the upgrade equipment plus the energy cost for the time horizon under the upgrade. For this reason, the total initial cost is always the energy cost of the legacy network.

We can gain some insight on the value of an energy market from these results. First consider the case of two operators in scenarios S_180_180 and S_220_100 used in Figures 1 and 2. Assume that a 30% reduction is imposed on the total energy of these two operators. At the time where the caps are set, both operators

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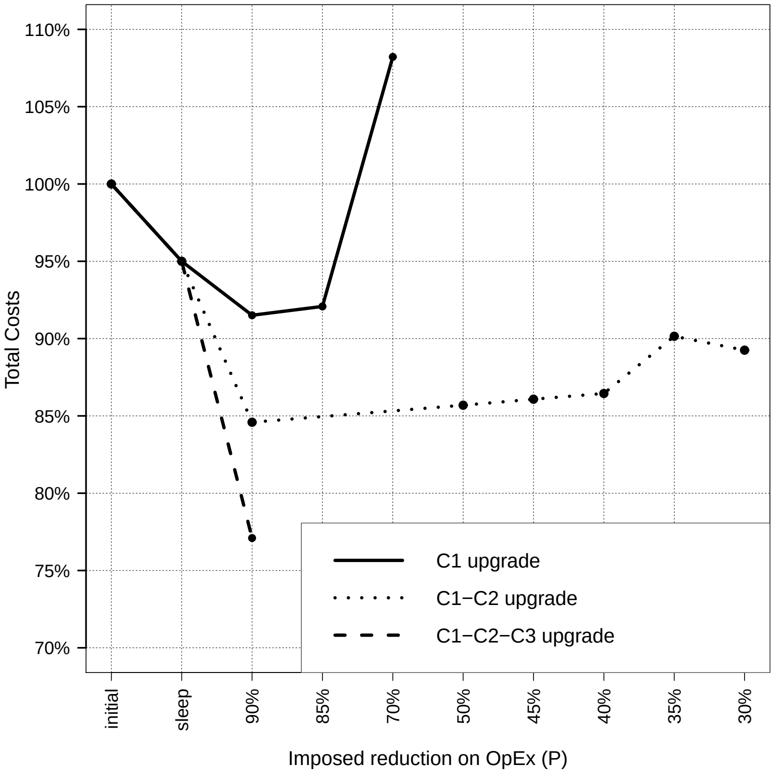
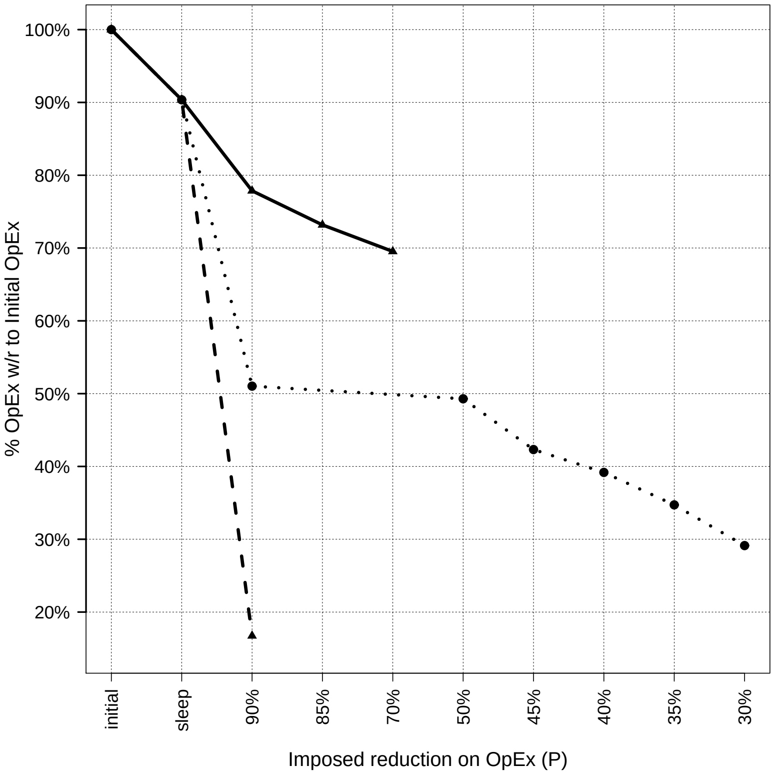
[3] In Figure 2a, the fact that the cost at -65 % is higher than the one at -70% is due to the large gap when the algorithm stops.

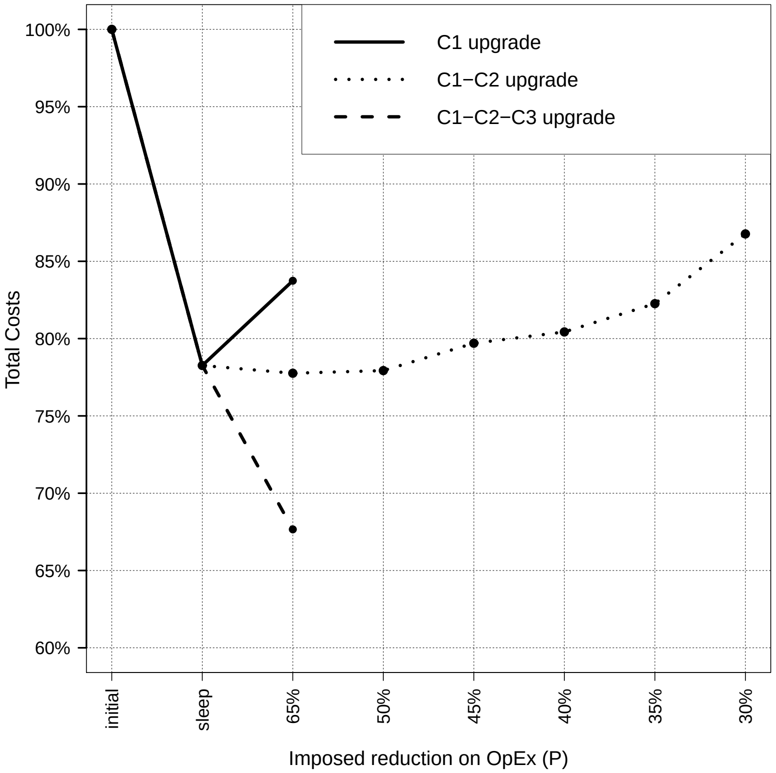


(a) *Total cost vs. Caps*

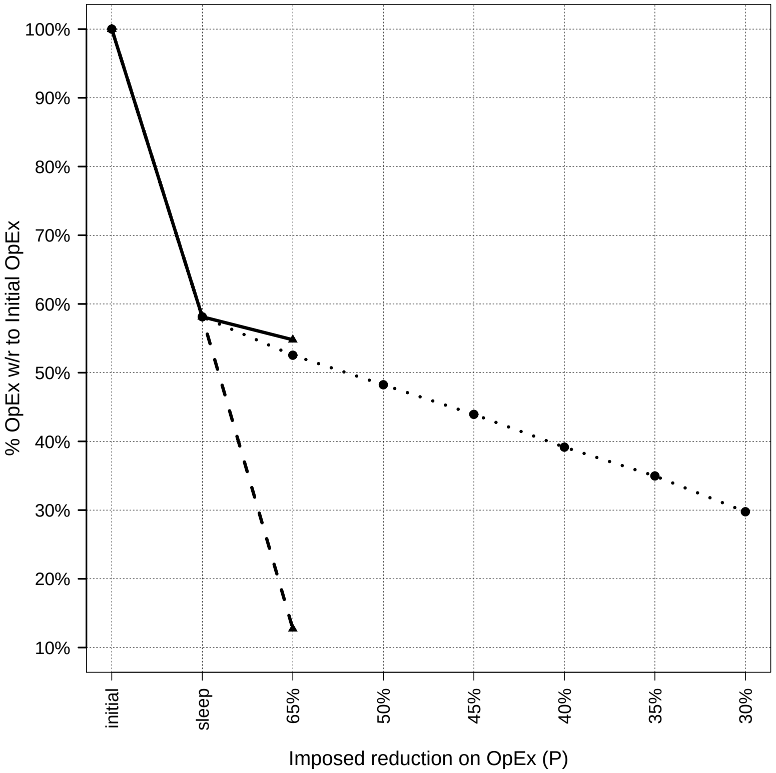


(b) *OpEx vs. Caps*

Figure 1: Scenario S_180_180



(a) *Total cost vs. Caps*



(b) *OpEx vs. Caps*

Figure 2: Scenario S_220_100

have the same kind of legacy network with only $C1$ technology and no energy management. Also assume that only $C1$ technology is available for upgrade.

Without a market, each operator is forced to meet the caps separately. This is easily done for the operator in S_220_100 simply by turning on the energy management, as can be seen from Figure 2b. On the other hand, it is much harder for the operator in scenario S_180_180. Enabling the energy management will only reduce the energy by about 10% so that a costly upgrade is needed, as displayed in Figure 1b.

Note however that the operator in S_220_100 has reduced its energy to a little less than 60% of C_0^e, which is more than what is required by the cap. An energy market would let the operators collaborate to take advantage of this feature, as displayed in Table 11. Here we show on the first line the initial total cost and the total OpEx of the legacy networks. Since we do not consider the legacy network CapEx C_0^c and we do not have any additional capital cost, the two values are the same and correspond to the sum of the two legacy networks' OpEx. The second line shows the total OpEx as required by the caps. The third line shows the results when each network has to meet the caps separately. The first part of the total cost is the upgrade cost of the operator in scenario S_180_180 to meet a 30% reduction. There is no extra capital cost for the other operator. To this, we add the OpEx cost to get the total. The OpEx value is the sum of the operation costs of the two upgraded networks. The interesting part is on the last line. Here, the network in scenario S_180_180 is upgraded to meet at least a 10% reduction of its own energy consumption, resulting in about 22% energy saving. It turns out that, when added to the reduction of the other network, this is more than enough to meet the global cap. In this case, however, the total cost is much smaller. In this particular case, there is no need for trading credits since the operator in S_220_100 meets the caps at no cost. Still, we need some mechanism by which the operator in S_180_180 would know that its counterpart has exceeded the cap and has some credit available. This would be taken care of by the carbon market.

Table 11: Separate vs market upgrades, scenarios S_180_180 and S_220_100, 30% reduction

	Total Cost (K€)	Total OpEx (K€)
Initial	1166	1166
Target OpEx	–	816
Separate	977	737
Market	810	780

We now present another example where some credit trading would be needed. Assume that the two network operators are operating in scenario S_220_100 and scenario S_120_60. At some time, a 20% energy cap is imposed. Both operators have already implemented energy management and the only technologies available are $C1$ and $C2$. We compare the total upgrade cost with and without a market system.

First, we show in Table 12 the results for upgrading a network in S_120_60. The first column shows the additional CapEx needed, the second one displays the value of the OpEx in the solution, the third represents the total incremental cost CapEx plus OpEx and the last one, the OpEx reduction that could be achieved. The first row shows the values for the legacy network. In that case, there is no incremental CapEx and the only expense is the OpEx, which is also the total cost. The corresponding values for a network in S_220_100 are shown in Table 13.

Table 12: Upgrade costs, scenario S_120_60

Add CapEx (K€)	OpEx (K€)	Total Cost (K€)	ΔOpEx (%)
0	267	267	–
30	214	244	20
30	211	242	21
60	188	248	30
90	174	264	35
120	155	275	42
160	132	293	51
190	116	307	56

Table 13: Upgrade costs, scenario S_220_100

Add CapEx (K€)	OpEx (K€)	Total Cost (K€)	ΔOpEx (%)
0	377	377	–
30	340	370	10
60	313	373	17
110	285	395	24
150	254	404	33
200	227	427	40
290	193	483	49

Without a market, each operator has to try to meet the requirement by itself. The network in S_120_60 can get a 20% reduction at a cost of 244 K€ while the network in S_220_100 has to go for a 24% reduction at a cost of 395 K€. Note that it is not possible to interpolate values since solutions are modular. Suppose now that there is a market. Because upgrade is relatively expensive, the network in scenario S_220_100 only upgrades for a 17% reduction at a cost of 373K€. This yields a total cost saving of 22 K€ with respect to the upgrade to 24%. This is compensated by the network in S_120_60 which is upgraded to a 30% reduction at a cost of 248 K€. This is a cost increase of 4 K€ with respect to the 20% upgrade. The results are compared in Table 14 where we show the total cost and OpEx from each case. It is clear that the overall cost is lower but in this case, the network in S_120_60 has incurred a higher cost than needed by the 20% caps and should be paid by the network in scenario S_220_100 at least 4 K€. This can only be done through some kind of market like energy trading.

Table 14: Separate vs market upgrades, scenarios S_120_60 and S_220_100, 20% reduction

	Cost (K€)	OpEx (K€)
Initial	644	644
Target OpEx	–	515
Separate	639	499
Market	621	500

6 Conclusion

We have been able to get some insight into three questions that network operators could ask when having to meet some energy caps. For this, we used an existing framework for the joint planning and energy management (JPEM) of mobile systems.

The first question was of how can an operator meet energy caps. We proposed two solutions: managing its network or improving it by installing new access devices. Using the JPEM framework, we computed the savings when energy management is turned on both for legacy and upgraded networks. For the cases we examined, we found that networks using only macro cells can easily reduce their energy use from 25% to 40% just by turning off some base stations in low-traffic periods. When upgrades are needed, we found that small-cell technology does make a very large difference in the upgrade cost.

We also found that the type of legacy base stations as well as the kind of technology available for network upgrades determine to a large extent the ability of a network to meet energy caps. In general, it will be very costly for an operator that has an efficient legacy network to comply with the energy caps. Inefficient networks, on the other hand, can do it at little or no cost.

Imposing an overall energy cap on different operators will thus lead to important fairness issues. One way out of this is to implement a trading device, like a carbon market, where networks that are already very energy-efficient can purchase low-cost credits from inefficient operators. We give two examples that show how the model can help quantify the savings brought about by the market.

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