Designing a hybrid renewable energy source system to feed the wireless access network

Designing a Hybrid Renewable Energy Source System to Feed the Wireless Access Network

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Abstract

Today, our society mainly relies on the energy generated by burning fossil fuels, which provides a reliable supply at an affordable price. However, this energy is not renewable and will eventually be depleted in the future. To address sustainability issues, we need to take action in all layers of our society, including our wireless access networks, which are still large power consumers. A possible solution in this field is the integration of RESs (Renewable Energy Sources) for the network supply. Nevertheless, since the production of these RESs is characterized by randomness, which is strictly dependent on the weather conditions, the network service may be compromised because of lack of energy for its supply. In this paper, we investigate the network's power performance i.e., how much power should be bought from the traditional electricity grid, when using either solar, wind, and geothermal energy or a combination of these three to feed the network (this is here called a multiple RES system). Furthermore, we propose a novel algorithm optimizing the (multiple) RES system accounting for the related CAPEX (Capital Expenditures) and OPEX (Operational Expenditures) costs. Our study shows that geothermal energy is the most reliable one, but also extremely expensive to invest in. Wind energy is the most appropriate choice - even for summer - since it is a rather cheap RES to invest in. The optimized multiple RES system performs the best as only between 0.4% and 11% (depending on the season) of the power required by the network should be bought from the

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traditional electricity grid.

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1. Introduction

Globally, the number of mobile subscribers have risen to 5.3 billion users and it is expected that by 2023 we will reach 5.7 billion subscriptions [1]. Besides the number of subscribers itself, also the speed of the connections have grown extremely: in 2018 the average network speed was 13.2 Mbps, while it is expected that this speed will more than triple by 2023. To support this increase in both subscribers and data rates, wireless networks need to expand and the first signs of antenna densification can already be noticed. [2] concludes that the ICT (Information and Communication Technology) GHGE (Global Greenhouse Gas Emissions) could grow from roughly 1-1.6% in 2007 to exceed 14% of the 2016-level worldwide GHGE by 2040. To put this in perspective, this would mean that the ICT sector is responsible for more than half of the current relative contribution by the whole transportation sector. In 2020, 24% of this contribution will be caused by the communication networks (incl. telecommunication networks). To counter this explosive GHGE footprint of the ICT sector, we must take measures on all different layers of the ICT industry, and more in particular of the communication network. As possible mitigation strategies, [2] proposes a combination of the use of renewable energy sources (RESs) like solar, wind, biomass or geothermal energy, tax policies, managerial actions and alternative business models. In this study, we address the RES used to feed the wireless access network. Currently, our networks are relying mainly on fossil fuels, which are not only responsible for larger carbon emissions, but are also not renewable and will deplete if we keep continuing like we are used today. Although renewable energy sources have some major advantages as mentioned above, there is also an important drawback of using renewable energy sources. RESs are not able to offer the same supply continuity as currently provided by fossil fuels or more traditional generators due to e.g., varying weather conditions. In this study, the performance of a wireless access network is compared for three different renewable energy sources: solar, wind, and geothermal energy. Furthermore, an algorithm is proposed that allows to optimize the network's energy provisioning system by combining the three aforementioned renewable energy sources.

Besides solar, wind and geothermal energy, there exists of course other RESs such as hydro power, biomass energy, and biofuels. Biofuels are mainly used for transportation applications and are hence out of the scope of this study. Although both hydro power and biomass energy are very reliable energy sources, they are extremely challenging to build either requiring a river that needs to be dammed up or because of the storage space for the organic materials (typically trees and plants). The aim of this paper is to build a RES system that can be installed and operated by the network operators themselves. As building new hydro power and biomass energy plants is already extremely challenging for utility companies and many can not even afford to do this, we do not consider these RESs as possible opportunities for the network operator.

Most studies in literature considering the use of renewables in telecommunication networks are focusing on the base station itself. Solar energy has received attention in the past [3, 4, 5, 6, 7]. All these studies conclude the same: solar energy is a very promising renewable energy source to use but needs to be combined with a significant battery system to intercept moments with no or limited solar production. Although the quality of batteries is slowly improving, they are still very expensive to invest in. To overcome this issue, several studies combined solar energy with at least one other renewable energy source. The obvious choice is wind energy [8, 9]. However, to the best of our knowledge, no study considers only wind energy to feed the base station and the wireless access network, making it difficult to fully address the issues that might occur when using wind energy. As even combining both solar and wind energy cannot avoid outages, researchers try to combine these renewables with water energy [10], (adiabatic compressed) air [11], or even an old-school (not environmentally friendly) diesel generator [12]. Recently, biomass has gained much attention and [13] proposes to power the base station by combining solar and biomass energy. So far, no study has considered geothermal energy. This is a promising renewable energy source that derives heat from within the sub-surface of the earth. Note also that the above-mentioned studies are only looking from a base station perspective. Only a few studies are addressing the bigger picture of the network's performance. [14] and [15] both consider the use of solar energy and the traditional electricity power grid on the performance of the network. [16] studies the network's performance when using both solar and wind energy.

The authors argue that to better address the variability, one should jointly consider the energy availability together with the dynamic characteristics of the load, that is exactly what we want to achieve with the algorithms proposed in this study as well as the inclusion of geothermal energy besides wind and solar energy. The major contributions of our study are:

- Studying and comparing the impact of solar, wind, and geothermal energy individually on the network's performance accounting for a realistic suburban environment. To the best of the authors' knowledge, this has never been done before for wind energy solely (so far always combined with solar energy and only on base station level) and geothermal energy.

- Combining the above-mentioned renewable energy sources i.e., solar, wind, and geothermal energy to feed the wireless access network.

- Optimizing the RES provisioning system for the wireless access network accounting for the traffic demand and the availability and cost of the different renewables (solar, wind, and geothermal). The goal is to minimize the amount of power that needs to be drawn from the traditional electricity grid.

- For each of the above contributions, we propose a novel algorithm designing the network accounting for both the energy availability and the user traffic demand.

The paper is organized as follows. In the next section, the methodology of our framework is described. In Section 3, we discuss the results for the individual RES systems, while Section 4 discusses the optimized RES system designed for our considered scenario. In Section 5, we give some recommendations on the design of multiple RESs system. Section 6 summarizes the most important findings of our study.

2. Methodology

2.1. Scenario

For this study, we consider a typical suburban area of 0.3 km^2 as shown in Fig. 1 (black outline square) [14]. The number of simultaneous active users varies during the day (based on confidential data retrieved from an operator). Fig. 1 gives an example (blue squares) for the worst case scenario (highest number of simultaneous active users) at 5 p.m. The users are uniformly distributed over the considered area meaning that every location in this area can be chosen as a possible location since this is a residential area (no hot spots). The users can either require a bit rate of 64 kbps (phone call) or 1 Mbps (data transfer). These users will be served by an LTE (Long Term Evolution) Advanced network consisting of 8 macrocell base stations (large red circles), each supporting 4 microcell base stations (small yellow circles). The same link budget parameters as in [14] are considered. The models of [17] are used for the power consumption of the macrocell and microcell Base Stations (BSs). Furthermore, we assume that the BSs are not consuming any power during sleep mode. A macrocell BS typically consumes 1672 W and a microcell BS 377 W. A traditional network design (where all macrocell and microcell BSs are always active) would result in a network power consumption of 25.4 kW. However, the network optimization algorithm introduced in this study is a capacity-based one, which means that it will respond to the instantaneous bit rate requirement of the user [18]. This results in an energy-efficient design compared to the traditional network design that typically over-dimensions the network. Since the network required power consumption will vary during the day (due to the varying number of users mentioned above), we will clearly show the network required power consumption at each moment for each considered case in the Results Section.

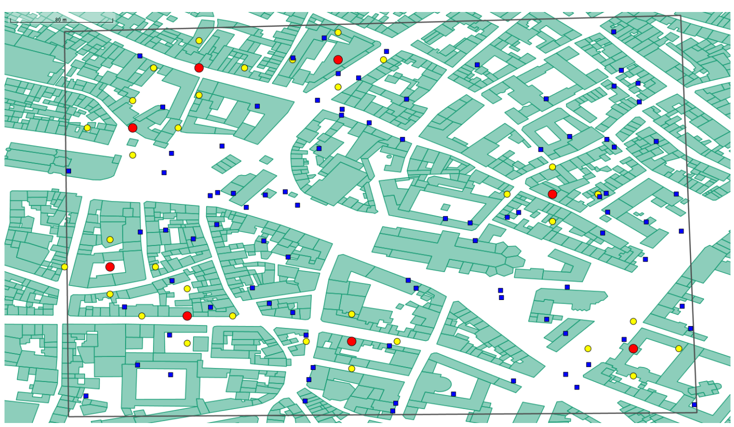


Figure 1: The considered suburban area of 0.3 km^2 (black outline square) with the base stations (red large circle = macrocell base station, yellow small circle = microcell base station and possible location of users for a worst case scenario at 5 p.m. (blue squares).

The network is powered by three possible renewable power plants (solar, wind, and geothermal), batteries, and the traditional electricity grid. The renewable power plants are shared among the network's BSs and power management decisions are made centrally for the whole network, meaning that they are based on the total available power over all the involved power plants and the total demand by the network regardless of the actual power plant implementation. More details on the renewable power plants can be found in the next section. The power generated by the power plants is first used to power the network and excessive power is saved on the batteries, according to a first-use-then-harvest principle. When there is no renewable energy available, the network can drain the power from the batteries. In case these are discharged, the network has to buy energy from the traditional electricity grid.

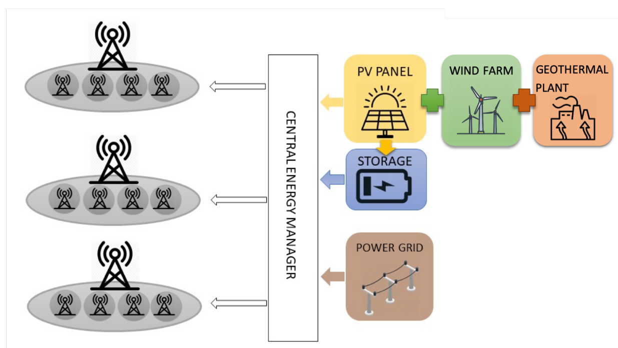


Figure 2: The energy provisioning and storage system architecture.

Since the seasonal weather influences the production of in particular the solar and the wind energy, we consider two different weeks for our simulations - one in summer (June 10^{th} till June 16^{th}) and one in winter (December 23^{rd} to December 29^{th}). Summer is the best case for the solar energy system, while winter is the worst. On the contrary for wind energy, the highest production is obtained during winter and the smallest during summer, while geothermal energy is not influenced by seasonal variations.

2.2. Problem description

As discussed above, our network consists of a set $\mathcal{N} = \{1, 2, ..., N\}$ of N users and K BSs with possible set $\mathcal{K} = \{1, 2, ..., K\}$. The input power of each BS can be set and is denoted with $\mathcal{P} = \{p_1, p_2, ..., p_K\}$.

$p_k \in \{0, 1, ..., p_t\}, \forall k \in \mathcal{K}$ is a discrete variable defining the input power of BS k with p_t the maximum allowable input power. The binary variable x_{kn} describes the assignment of user n with BS k as follows:

$$x_{kn} = \begin{cases} 1 & \text{if user } n \text{ is assigned to BS } k \\ 0 & \text{otherwise} \end{cases}$$

The binary variable y_k defines whether BS k is active or not:

$$y_k = \begin{cases} 1 & \text{if BS } k \text{ is active} \\ 0 & \text{otherwise} \end{cases}$$

The solution will thus be defined as an integer vector that contains the active or not BSs, the input power and the users associated.
The problem can be formulated as follows. We want to design an energy-efficient wireless access network and a suitable RES system that minimizes the amount of energy required from the traditional electricity grid while serving at least 95% of our users. Mathematically, the problem can be expressed as follows:

$$\begin{aligned}
\text{P1: } \min_{y,p} \quad & \sum_{k \in \mathcal{K}} P_{el}(y_k p_k) \\
\text{s.t. C1:} \quad & y_k \in \{0, 1\}, \forall k \in \mathcal{K}, \\
\text{C2:} \quad & p_k \in \{0, 1, ..., p_t\}, \forall k \in \mathcal{K}, \\
\text{C3:} \quad & x_{kn} \in \{0, 1\}, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}, \\
\text{C4:} \quad & \sum_{k=1}^{K} x_{kn} = 1, \forall n \in \mathcal{N}, \\
\text{C5:} \quad & \frac{\sum_{j=1}^{K} \sum_{i=1}^{N} x_{ij}}{N} \geq 0.95, \\
\text{C6:} \quad & \sum_{k \in \mathcal{K}} (P_{el}(y_k p_k) + P_{RES}(y_k p_k) + P_{bat}(y_k p_k)) = \sum_{k \in \mathcal{K}} (P(y_k p_k), \\
\text{C7:} \quad & max \sum_{k \in \mathcal{K}} (P_{RES}(y_k p_k) + P_{bat}(y_k p_k))
\end{aligned}$$

with $P_{el}()$ the power obtained by the network from the traditional electricity grid. Constraints C1, C2, and C3 indicate, respectively, whether BS k is active, the input power of BS k, and the users connected to BS k. Constraint

C4 expresses that a user can only be connected to one single BS, while constraint C5 ensures that a user coverage of at least 95% is always achieved. Constraint C6 ensures that the consumed power by the network from the traditional electricity grid, the renewable energy sources $P_{RES}()$, and the battery $P_{bat}()$ does not exceed the network's power consumption $P()$ while maximize the power consumed from the renewable energy sources and the battery (constraint C7).

2.3. Energy provisioning and storage system

As mentioned above and shown in the proposed framework of Fig. 2, the network is powered not only through the traditional electricity grid, but also through three renewable energy plants: a solar, wind, and geothermal plant. For this renewable energy generation system, data is obtained from the official website of Terna S.p.A [19] which is a system operator managing the Italian energy production system. The operator reports on the hourly production of all the RESs installed on the Italian territory. The settings of our renewable energy provisioning system are as follows:

- Solar energy - Nominal capacity of a PV (Photo-Voltaic) panel: 12.5 kWp [14]
- Wind energy - Nominal capacity of a wind turbine: 2.5 MW
- Geothermal energy - Nominal capacity of the whole geothermal plant: 21 MW

Fig. 3 gives an overview of the power produced by each RES during the considered weeks in summer and winter. Note that for the geothermal power plant, we can claim only a certain percentage (maximum 20% is assumed) of the total production since this power plant is typically shared between different operators because of its high costs as we will discuss below. Although we are using real-time predictions of the renewable energy sources, we are aware that the behaviour of renewable energy is stochastic and intermittent [20]. Therefore, ideally, the approaches discussed here should be combined with a time window that takes into account future predictions of the renewable energy production, allowing a more intelligent decision at that moment in time. The effect of using such a time window on the design of the network is thoroughly discussed in [14]. However, since the above-mentioned study only considers solar energy and a profound study of the time window is beyond the scope of this study, no time window was considered here.

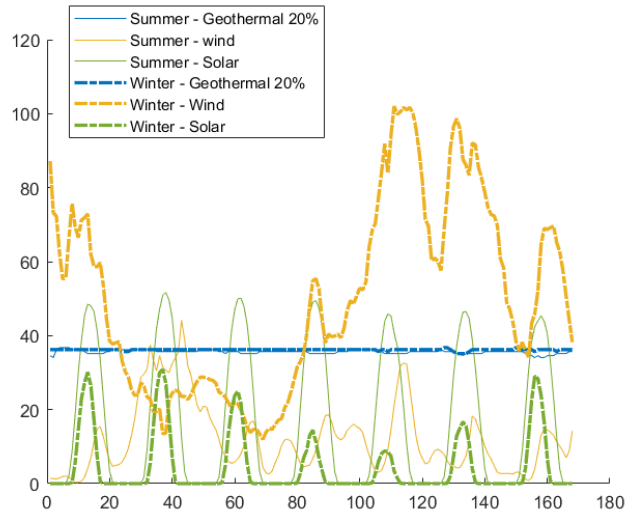


Figure 3: RES power production (20% of a 21 MW geothermal plant, a 2.5 MW wind turbine, and a 100 kWp PV system) for summer (full lines) and winter (dashed lines) [19].

For each RES, we define an installation cost, an Operation and Maintenance (O&M) cost and a capacity factor as shown in Table 1 [21]:

- *Installation cost* [EUR/kW]: the cost to develop and provide durable assets, including machinery or intellectual property. Typically this cost is not fully deducted in the accounting period they were incurred, but rather amortized over the system's lifespan.

- *O&M cost* [EUR/kW/year]: the cost to keep the system smoothly operating, typically fully deducted in the accounting period.

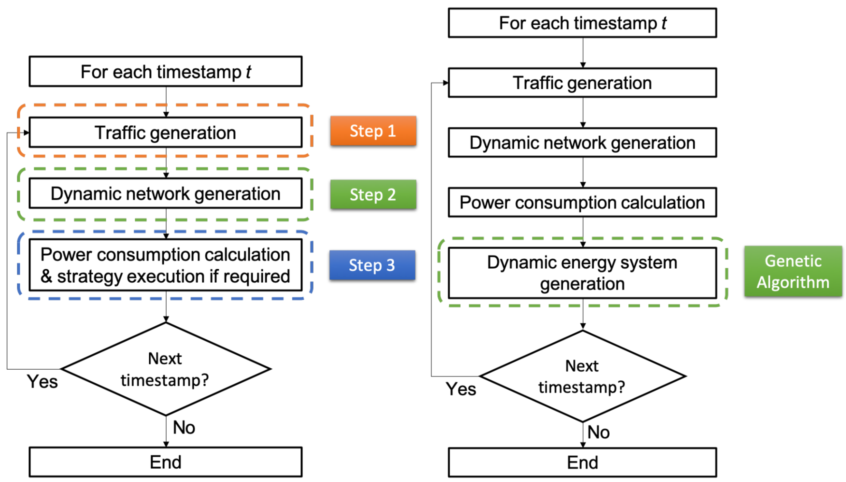
- *Capacity factor* [%]: defines the actual electricity production divided by the maximum possible electricity output of a power plant over a certain period of time.

These costs will be accounted for when designing the multiple RES system in the second part of this study.

As shown in Fig. 2, besides the RES provisioning system, there is also an energy storage available. Unless mentioned otherwise, this energy storage is a battery of 50 kWh which is assumed to be fully charged at the start of our simulations [14].

RES	Installation cost [EUR/kW]	O&M [EUR/kW/year]	Capacity factor [%]
Solar	2375	15	16
Wind	1900	30	29
Geothermal	3700	110	85

Table 1: Installation cost, O&M cost, and capacity factor for the considered RESs [21].



(a) (b)

Figure 4: Flow diagram of the algorithms for dynamic network design (a) and dynamic energy system generation (b).

2.4. Deployment tool

This study consists of two parts. In the first part we will investigate the influence of using a single RES on the power performance and in the second part we will focus on optimized design of the multiple RESs system. Fig. 4(a) and 4(b) shows the algorithms used for the simulation of the first and the second part of this study, respectively. Note that for both studies, it is assumed that all BSs are in sleep mode at the start of the algorithm and that the battery is fully charged.

For the first part of the study, the algorithm of [14] is expanded with the RES production models of Fig. 3. The algorithm requires the following input:

- Area to cover: a 3D shape file containing all the buildings in the envi-

Input	**Value**	**Variable?**
Considered area	0.3 km^2	—
Area type	suburban	—
User bit rate	64 kbps (voice) & 1 Mbps (data)	—
Number of users	Depending on timestamp	—
User location distribution	uniform	—
Macrocell BSs	8	[0, 1, ..., 8]
Microcell BSs	32	[0, 1, ..., 32]
Duration simulation	1 week (168 time stamps)	—
Solar energy	12.5 kWp	[0, 12.5, ..., 100]
Wind energy	12.5 MW	[0, 2.5, ..., 15]
Geothermal energy	4.4 MW	[0, 0.6, ..., 21]
Battery	50 kWh Fully charged at t = 0	—

Table 2: Summary of the fixed and variable input data.

ronment (used to determine whether a user is in line-of-sight or not of a certain base station).

- List of possible BSs locations
- Number of users: as mentioned above the number of users depends on the moment of the day. For each considered timestamp, the number of users needs to be defined.
- Bit rate requirement: determines the bit rate required by the user.
- Location distribution: determines the location of each user.

Table 2 summarizes the required input for the algorithm. It also mentions how the parameters can be varied (if applicable) for the second part of our investigation.

The deployment tool consists of three steps:

Step 1. *Traffic generation*: for each time stamp the traffic is generated. Each time stamp corresponds with a certain number of simultaneous active users. A location within the considered area is assigned to each user, as well as a bit rate requirement as discussed in Section 2.1 and shown in Table 2.

Step 2. *Dynamic network generation*: in this step, each user is (if possible) connected to the BS from which it experiences the lowest path loss (and below the maximum allowable one) that can still offer the required bit rate. We prefer to connect the user to an already active BS since this is more energy-efficient [18]. Only when this is not possible a new BS will be activate. Each time stamp is 25 times simulated with different seed because the design of the network highly depends on the location and bit rate of users. As we focus in this study on the energy provisioning system of the network and how it is accounted for in the network design phase (see next step), we refer to [14, 18] for a thorough description of the network design algorithm, as this part of the algorithm has not been changed.

Step 3. *Power consumption calculation*: once the network is designed, we can calculate how much power is required for its operation. In case more power is required than available through the RES provisioning system and storage, the additional power will be bought from the traditional electricity grid. In case more (renewable) power is available than required, the power will be saved on the battery. All the power that cannot be saved on the battery is considered to be wasted. Note that for current wireless access networks, this power consumption fully relies on the traditional electricity grid without accounting for the fact whether this is green energy or not.

To design the optimal RES provisioning system, the novel algorithm shown in Fig. 4(b) is used. The first two steps, traffic generation and dynamic network generation, remain the same, followed by determining the network's power consumption. Once this is known, the optimized RES system can be designed (green block in Fig. 4(b)). To this end, a genetic search algorithm has been implemented. In a genetic algorithm, a *population* of candidate solutions as shown in Fig. 5 - evolves towards a better solution. A chromosome is made up of a set of characteristics, known as *genes*, which is typically a binary value. For our problem, each RES is represented by 3 genes as shown in Fig. 5. This means that each RES can take 3 bytes, allowing to differentiate between 8 different sizes for that particular RES system:

- Solar: from 0 to 100 kWp in steps of 12.5 kWp
- Wind: from 0 to 7 wind turbines (each of 2.5 MW) in steps of 1

Figure 5: Population pattern for a genetic search algorithm.

- Geothermal: from 0 to 21% share of a 21 MW power plant in steps of 3%

To create a next generation chromosome, a genetic algorithm takes two parents from the current solutions, and swaps certain genes between them to create a new solution. This swapping is done in three steps that are discussed in detail below: selection, crossover, and mutation. Our simulations show that the algorithm should generate 10 populations to allow a good convergence for our results. From this 10th generation population, the chromosome with the highest fitness value is the final solution. We discuss below how this fitness value is determined.

2.4.1. Selection, crossover and mutation

The idea of the selection phase is to choose the fittest individuals and let them pass their genes to the next generation. There many different techniques which can be used for selecting the individuals. The most suitable for our problem are:

1. *Elitist selection*: guarantees that the fittest members of each generation are selected.
2. *Tournament selection*: chooses subgroups of individuals from the larger population and lets members of each subgroup compete against each other. Only one individual is chosen from each subgroup to reproduce. This selection is applied twice here to choose two individuals, becoming the parents for the following generation.

After selecting the individuals which will be used as parents for creating the population of the next generation, *crossover* is applied, producing a new offspring born from the fusion of the parents. For each pair of parents that will be matched, a crossover point is chosen. This is typically a single locus at which the alleles are swapped from one partner to each other. For our problem, we consider each gene as a possible crossover point. The crossover rate here chosen is thus 0.5: the probability to pick one gene from parent 1 or parent 2 is uniform. Once a new offspring is born, some of its genes can be subjected to a *mutation* with a low probability. This implies that some of the genes can be flipped. Mutation occurs to maintain diversity within the population and prevent premature convergence. A value of 0.015 is considered for our study.

2.4.2. Fitness function

To evaluate the performance of a solution (or chromosome) a fitness function is typically used. The candidates with a good fitness have a high probability to get selected. Here we want to select solutions that minimize the energy cost and the energy waste. Therefore, the fitness function f is defined as follows:

$$f = LCOE \times E_{prod} + \begin{cases} 0.29 \times (E_{needed} - E_{prod}), & \text{if } E_{bought} > 0 \\ LCOE_{mean} \times (E_{prod} - E_{needed}), & \text{otherwise} \end{cases} \quad (1)$$

with E_{prod}, E_{needed}, and E_{bought}, the power that is produced by the RES system, the power required by the network and the power that needs to be bought, respectively. $LCOE$ is the Levelized Cost of Energy which is an economic assessment of the average total cost to build and operate a power generating asset over its lifetime divided by the total energy output of the asset over that lifetime [22]:

$$LCOE = \frac{CRF \times ICC + AOE}{AEP_{net}} \quad (2)$$

with CRF the capital recovery factor, which is a ratio used to calculate the present value of an asset, ICC the installed capital cost or expenditures, AOE the annual operating expenses i.e., operational expenditures, and AEP_{net} the annual energy production.

2.5. Metrics

To evaluate the performance of the different and combined RES systems, the following metrics are considered:

- *Power consumed* [kW]: describes how much power the designed network consumes.
- *Power produced* [kW]: indicates how much power is produced by the individual or multiple RES system.
- *Power stored* [kW]: shows how much power is stored at the battery. The value can never been higher than the storage size.
- *Power available* [kW]: equals the sum of the power produced and the power stored.
- *Power wasted* [kW]: defines how much power is produced that will not be consumed by the network nor it can be stored due to a fully charged battery.

The above metrics can either be evaluated for a single timestamp or for a predefined time span. In case of the latter, we will clearly mention this by referring to it as the total value.

3. Results

3.1. Individual RES systems

In this section, we investigate the performance of the single RES system. For this study, the algorithm of Fig. 4(a) is used. Table 3 gives an overview of the power produced, bought, and wasted during winter and summer for the different RES systems.

3.2. Solar energy

For an in-depth analysis of solar energy, we refer to [14]. Compared to the SOTA (State Of The Art) architecture where no renewable energy source is used and hence all power should be bought, only 83.2 kWh of power (or 6.5% of the total required power) should be bought during the summer thanks to the sunny climate in Italy. During the winter, about 38.4% of the required power should be bought. Typically, the power needs to be bought during the

	Winter			Summer		
RES system	Produced	Bought	Wasted	Produced	Bought	Wasted
Solar - 100 kWp	784.5 kWh	38.4%	25%	2806.7 kWh	6.5%	67%
Wind - 5 windmills	825.2 kWh	31.3%	8.2%	204.2 kWh	80.1%	0%
Geothermal - 20%	607.7 kWh	50.2%	0.03%	607.7 kWh	50.2%	0.03%
Optimized	1227.3 kWh	0.4%	0.2%	1379.7 kWh	13.7%	0%

Table 3: Comparison between the optimized multiple RES system and a single RES system. Delta represents the difference in percent points between the single and optimized RES system.

night when no sunshine is available and the excessive power produced during the day can not be stored due to storage limitations. This is clearly reflected in the energy wasted: during summer 67.0% is wasted due to a fully charged storage. During winter, this decreases to 25.0% which is still a significant amount of power that is completely wasted. Based on the amount of wasted energy, one can conclude that the PV system is oversized or the batteries are under-dimensioned. Nevertheless, still some power needs to be bought. Using more PV panels will significantly decrease the amount of power bought (2.5% and 25.0% for summer and winter, respectively, when using 8 panels) but this can only be done when significantly increase the battery storage (when using 8 panels, up to 95.6% of the produced power is wasted during summer).

3.2.1. Wind energy

Fig. 6 shows the evolution of the consumed (blue), produced (green full), stored (purple), and wasted (red) power during the considered week in winter. During this week, the 5 wind mills produces about 825.2 kWh in total. Although the network consumes about 1275.7 kWh in total, unfortunately 8.2% (or 13.8 kWh) of this produced power is wasted due to a fully charged battery. This can be noticed in Fig. 6 in the beginning of the week (t = 0 to 9), between t = 123 and 133 and t = 140 to 151. Due to the waste and the fact that there is not enough power produced by the 5 wind mills, the operator will need to buy 31.3% (or 398.8 kWh) of the required power from the traditional electricity grid. Note that in total this accounts for only 95% (= 825.2 kWh produced - 13.8 kWh wasted + 398.8 kWh bought) of the 1275.7 kWh of required power. However, one can also rely on 50 kWh of power stored on the battery since we assume a fully charged battery at the start of the simulation.

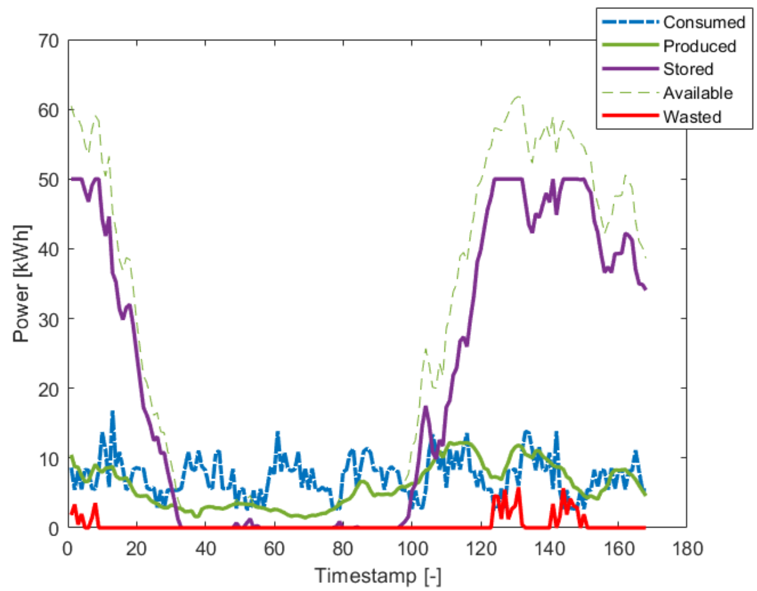


Figure 6: Evolution of the power consumption, the power production, the power stored, the available power (= power produced + stored), and the wasted power during the considered winter week when using 5 wind mills.

As can already expected from Fig. 3, the performance of the wind energy is worse in summer than in winter. During the summer week, only 204.2 kWh is produced. Luckily no energy is wasted, but this still requires a purchase of 80.1% (or 1022.1 kWh) of the required power from the traditional electricity grid to keep the network fully operational. This result might indicate that it is beneficial to use more wind mills, especially during the summer season. Fig. 7 shows the total amount of power bought and wasted as a function of the number of wind mills for both winter and summer. As one could expect, the amount of bought power decreases with an increasing amount of wind mills: when adding 5 more wind mills (so 10 wind mills in total), only 65.4% or 834.1 kWh (-14.7 pp) and 10.9% or 138.6 kWh (-20.1 pp) should be bought in, respectively, summer and winter. Although it might be interesting to have more wind mills, there is also a downside during the winter season which is not present during summer. If we use more than 5 wind mills, the amount of energy that is wasted starts to increase as well. About 1/3th (or 548.7 kWh) of the produced power is wasted when using 10 wind mills in winter. This rather negative effect can be solved by using a larger but more expensive battery. Note also, that in more urban environments it might not be easy to find enough space to install a park of 10 wind mills. Hence, we recommend to use a maximum of 5 wind mills of 2.5 MW to cover an area similar in size as the one here considered if wind energy is the only renewable energy source available.

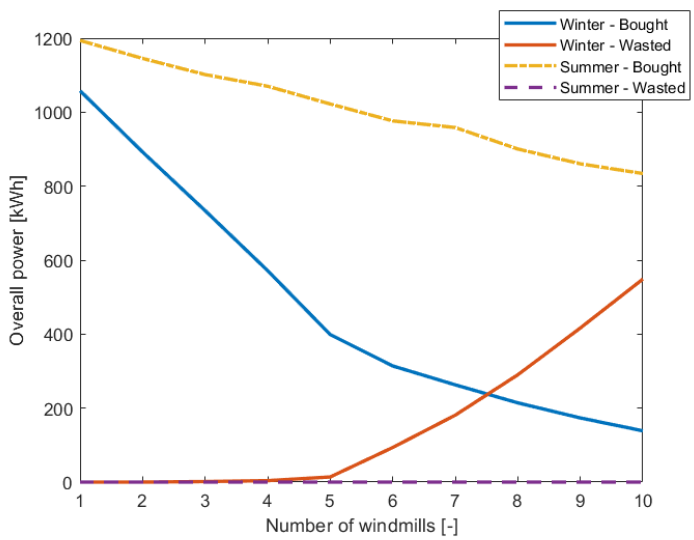


Figure 7: Total energy bought and wasted during winter and summer as a function of the number of windmills.

3.2.2. Geothermal energy

We now analyze the performance of the geothermal energy. Since the energy provisioning through geothermal energy does not significantly fluctuate both over time and the season as shown in Fig. 3, we have limited this analysis to winter time only. Similar results will be obtained for the summer season. Fig. 8 shows the evolution of the consumed (blue), produced (green), stored (purple), and wasted (red) energy during the considered winter week when using a 20% share of a 21 MW geothermal energy plant. Due to the more or less constant energy production (about 3.6 kWh for a single timestamp, resulting in a total production of 607.7 kWh) which is about 47.5% of the required energy, the battery never gets charged again after depleting the initial charge. Only a very limited amount of 0.2 kWh of energy is wasted during the first timestamp. This means, however, that about half of the

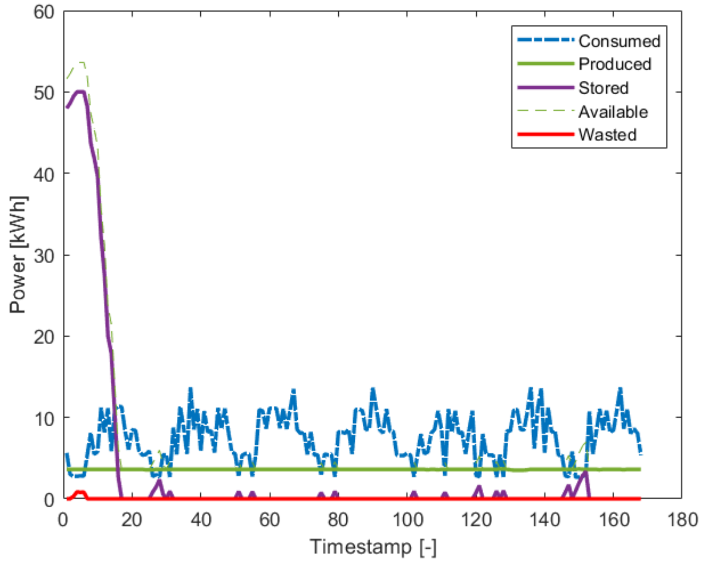
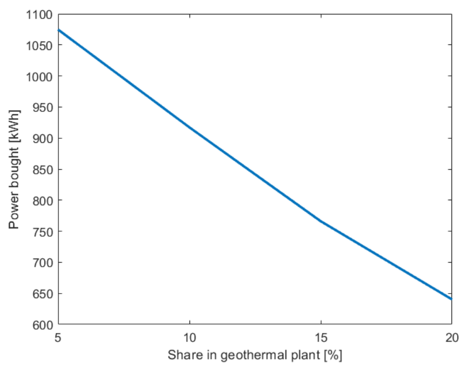


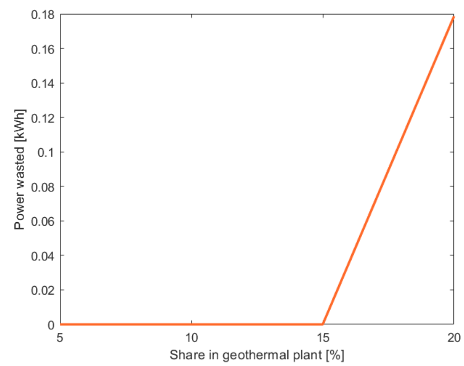
Figure 8: Evolution of the energy consumption, the energy production, the energy stored, the available energy (= energy produced + stored), and the wasted energy during the considered winter week when using 20% share of a geothermal plant.

required energy (or 640.1 kWh) still needs to be bought from the traditional electricity grid to keep the network fully operational.

Based on the above-mentioned results, one can of course argue that a larger share in a power plant should be used for the considered network size. Fig. 9(a) and 9(b) show the amount of power bought from the traditional electricity grid and the amount of energy that is wasted, respectively, as a function of the share in the geothermal plant (in steps of 5%). As expected, a higher share in the geothermal plant results in a lower amount of bought power. When increasing the share by 5%, the amount of bought power decreases with about 16% (917.2 kWh vs. 766.1 kWh for 10% and 15%, respectively). When the share is higher than 15%, a limited amount of renewable energy is wasted as already mentioned above (0.2 kWh for 20%). Considering the fact that geothermal energy is a very expensive renewable energy source to invest in (cfr. Table 1) and the fact that from a 20% share on, we are start to waste some energy, we do not recommend to use a higher share for the considered network but rather combine geothermal energy with another cheaper renewable energy source like wind or solar energy as we will



(a)



(b)

Figure 9: Amount of power bought (a) and wasted (b) as a function of the share in a geothermal power plant.

discuss later on, where we will also account for the CAPEX and OPEX cost of each energy source.

4. Full framework

In this section, the full framework is used. This means that for every hour not only the network is optimized towards the user traffic but also, based on the network's power consumption, also the RES system is optimized by choosing which and how many RESs to use, accounting as well for the related OPEX and CAPEX (Sec. 2.3). For this study, the algorithm of Fig. 4(b) is used. To the best of the authors' knowledge, using a mixture of various RES, as well as optimizing them, to feed the wireless network has not been done before. The actual implementation of such an RES system is of course beyond the scope of this study, but we assume that all chosen RESs are placed in a single energy park from which the network can drain electricity.

4.1. Winter

Fig. 10 shows the power consumed, bought, and wasted during the considered week in winter. During the week, the network consumes about 1280 kWh in total. The network's power consumption is the largest during daytime when the highest number of users is active in the area, and the lowest during night time as shown by the purple line in Fig. 10. Only 0.4% of this total power consumption i.e., 5.6 kWh, should be bought from the traditional electricity grid (red line). This means that the network can operate almost independently of the traditional electricity grid. An energy shortage typically occurs during the night when no solar energy is available and the geothermal and wind energy is also not sufficient. Not only the energy shortage is limited in this scenario, also the energy wasted is limited (blue line). Only 2.65 kWh of power could not be stored on the batteries. This happens especially in the beginning of the week and thus of our simulation. This is due to the fact that we assume that the batteries are fully charged at the initial phase of our simulation. During the week, the effect of this decision is smoothed and no energy is further wasted. The color bars in Fig. 10 show for each time stamp the amount of power that is provided by each RES. Wind energy (green bars) is the RES that is chosen at almost every time stamp, combined with a small amount of geothermal energy (orange bars). Solar energy (blue bars) is the least popular RES during winter time as it is only utilized for a few time stamps during the day. In winter there is not enough sunshine not only due to the more cloudy seasonal weather but also because of the "shorter days" than in summer [14].

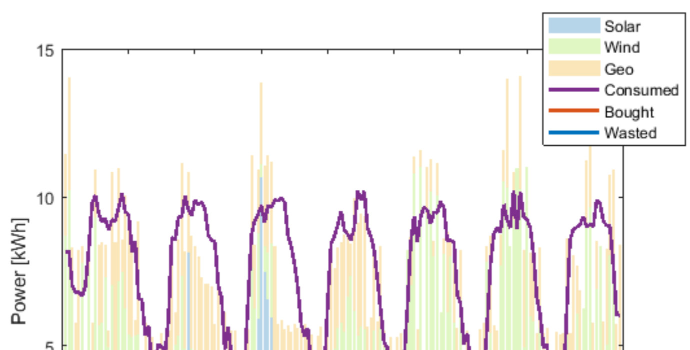
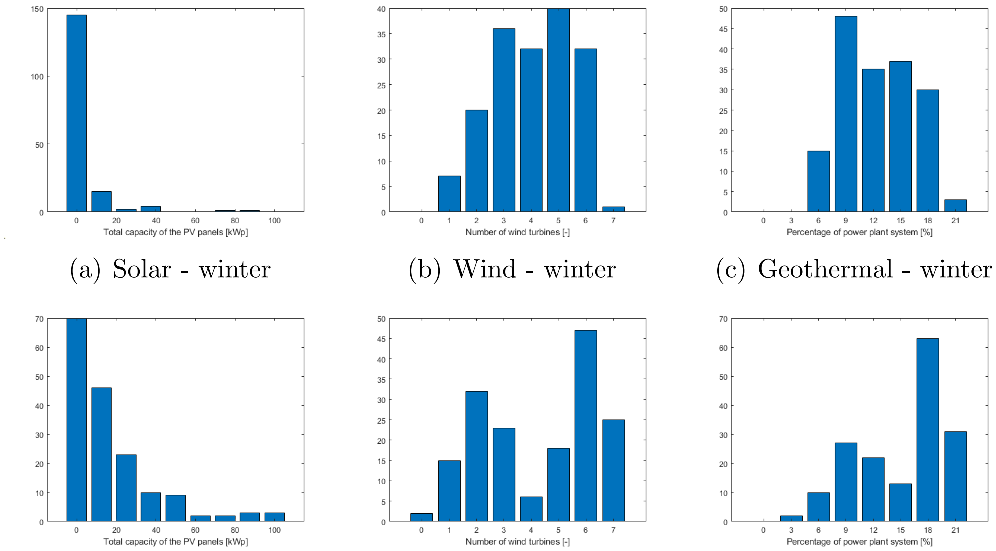


Figure 10: Evolution of the network's power consumption, the renewable power production, the power bought from the traditional electricity grid, and the power wasted during the considered week in winter.

In Fig. 11 (a,b and c), we plotted the histogram for the size of, respectively, the solar, wind, and geothermal system during winter. It is clear that,



(a) Solar - winter (b) Wind - winter (c) Geothermal - winter

(d) Solar - summer (e) Wind - summer (f) Geothermal - summer

Figure 11: Histogram of each RES system size chosen by the optimization algorithm during winter (a-c) and (d-f), determined over 25 simulations.

for winter time, it is recommended to not use any PV modules or only a very small portion up to 20 kWp. Wind energy is a very good choice, especially since the winter season allows to produce a significant amount of power (about 728.8 kWh) by the wind turbines. For a small network like the one we consider, about 5 wind turbines of 2.5 MW should be sufficient. The rest of the power can be provided by 9 up to 18% of a 21 MW geothermal plant (about 421.6 kWh).

4.2. Summer

Fig. 12 shows the results for the considered week during the summer. The network's power consumption (purple line) is of course the same as during the winter period since the same traffic is assumed for both periods. Remarkable is that in this case a significant amount of power needs to be bought (red line) from the traditional electricity grid: about 13.7% or 188.5 kW which is an increase of 10.6 percent points compared to the winter period. As mentioned in Sec. 2.3, the predictions for the power production are for an Italian climate which is very sunny during the summer months. Therefore, mostly solar energy (blue bars) is used compared to the winter period. The network's power consumption during day time is mainly covered by the PV panels but there is not enough power produced to be stored at the batteries so the night time can be covered as well [14]. This is also confirmed by the fact that no power at all is wasted (blue line) during this week. The designed wind and geothermal systems are also not large enough to cover the night time energy shortage. Over the whole week period, no power is wasted compared to the winter period where a limited amount of 2.7 kWh is wasted.

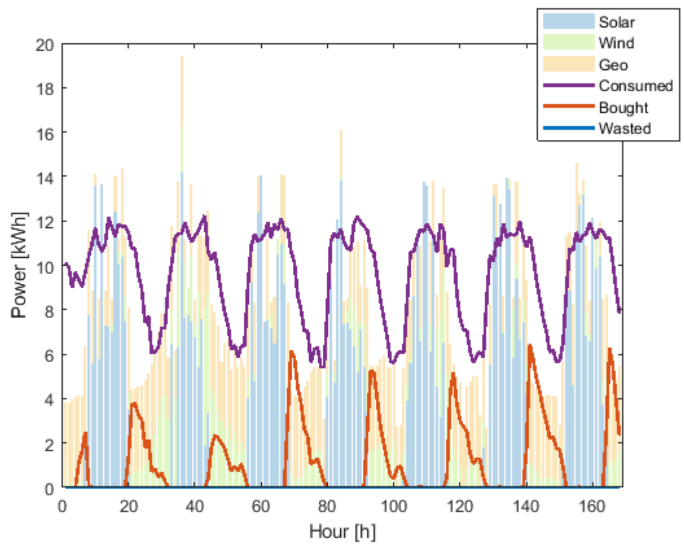


Figure 12: Evolution of the network's power consumption, the renewable power production, the power bought from the traditional electricity grid, and the power wasted during the considered week in summer.

Fig. 11 (d,e,f) shows the recommended size for, respectively, the solar, wind, and geothermal power plant. A solar plant of up to 30 kWp should here be combined with 6 wind turbines and 18% of a 21 MW geothermal plant. In fact, a rather larger wind system is preferable over the other sources. Since we are considering a summer period, one would of course expect large quantities of solar panels. However, they are kept quite small (about 30 kWp), since larger modules lead to production peaks during the day. These kinds of solutions are penalized by our algorithm for wasting too much energy.

5. General recommendation considering the RES system

Table 3 compares the amount of power bought when using the optimized multiple RES network and when using only one type of RES (assuming the highest production capacity here considered). For winter, our optimized system performs the best, followed by wind energy and solar energy (+10.5 pp and +20.5 pp, respectively). During summer, our optimized RES system performs again the best, followed by solar energy (+27.4 pp). Wind energy performs significantly worse than our optimized RES system (+ 54.4 pp bought power) due to the absence of wind in summer. Although geothermal energy performs the worst of all considered systems (+49.8 pp and +39.2 pp power should be bought in winter and summer, respectively), Table 3 clearly shows that geothermal energy is the least dependent on variations in the weather conditions: both in winter and summer about half of the required power should be bought from the traditional electricity grid.

When implementing the multiple RES system, one has of course to choose for one system with a trade-off between the system optimized towards the winter and towards the summer. Based on the histograms of Fig. 11, the following recommendations regarding the RES system are made (assuming a 50 kWh power storage):

- Wind energy (Fig. 11 (b) & (e)): is the most appropriate choice, even for summer where the presence of the wind is much lower. This is due to the fact that it is a rather cheap RES to invest in as shown in Sec. 2.3. For the considered scenario, a good choice is to use 5 to 6 windmills of 2.5 MW each. However, for a wind park of this size about 2.5 to 3 km^2 of space is required [23]. Another rule of thumb is that each wind turbine should be placed 150 m away from any nearby obstruction as well as at a height such that the bottom of the rotor blades will be 9 m above the obstructions (incl. buildings and trees).

- Geothermal energy (Fig. 11 (c) & (f)): as mentioned above geothermal is a trustworthy RES since its production is the most constant in time as it is independent of the seasonal weather like wind and solar energy. However, it is a very expensive RES to invest in. Note that this RES requires drilling in the bottom, hence limiting the possibilities to place a geothermal power plant (e.g., more difficult in a city environment). Based on Fig. 11, we recommend to use between 9% up to 18% of a 21 MW power plant for the considered scenario.

- Solar energy (Fig. 11 (c) & (f)): especially in countries with a sunny climate in summer, it can be interesting to add up to 20 kWp PV panels. This requires about 100 m^2 [14] space for implementation, but the advantage compared to the other RES systems is that this does not necessarily needs to be free space. The PV panels can also be placed on e.g. the roofs of buildings.

The advantage of investing in such a multiple RES system by the network operator is two-fold: (i) the network's provisioning does not longer rely on the provisioning through a utility company which makes it less vulnerable for increasing energy prices and possible blackouts, and (ii) it protects the further depletion of our fossil fuels.

6. Conclusion

Wireless access networks are currently still large power consumers. To protect our fossil fuels, renewable energy sources can be considered to feed the network. One of the drawbacks of especially solar and wind energy are the large fluctuations in provisioning due to the varying weather conditions. Geothermal energy has a more reliable production but is expensive to invest in. In this study, we propose a novel framework where a multiple RES system - combining solar, wind and geothermal energy - is used to feed the wireless access network. The framework optimizes the different RES systems (solar, wind and geothermal energy as well as the size of the system) in order to minimize the amount of power that needs to be bought from the traditional electricity network (hence using fossil fuels), while accounting for the CAPEX and OPEX costs related to each considered RES. When using the optimized multiple RES system, between 0.4% and 11% of the required power should be bought from the traditional grid (while all required power should be bought by the current networks) depending on the considered season. Between 6.1 pp and 54.4 pp less power should be bought compared to the individual RES systems. The optimal RES system consists of 5 to 6 windmills of 2.5 MW each, between 9 to 18% share in a 21 MW geothermal power plant, supplemented with up to 20 kWp solar panels, especially for those countries with a very sunny climate. One of the issues with renewable energy provisioning is the storage of the excessive energy that is produced. Batteries are currently still very expensive and their quality is sometimes questionable. To save some extra money, a sell and buy system could be used with the operator. Since the network has already a connection to the traditional electricity grid to buy power when required, the excessive power produced by the operator's RES system can be sold back to the utility company. Using such an approach requires of course a full integration of the network into the city's smart grid. As future work, such a sell and buy system will be introduced to our framework, as well as the smart grid integration.

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