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Assessing the Integration of Biomass Gasification and High-Power Charging Stations for Battery Electric Buses: A Case Study in the City of Carpi

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ABSTRACT

The shift to electric vehicles in transportation is essential to mitigate pollution and achieve global climate goals. Recent EU regulations and incentives have accelerated the adoption of this strategy, especially in cities, facilitating the development of fleets of electric city buses. This paper explores the integration of biomass gasifiers and battery energy storage systems to develop environmentally sustainable high-power charging stations, focusing on Carpi, Italy, as a case study. By using locally available biomass resources, this approach aims to disconnect power from the electricity grid and reduce emissions. Through the analysis of different configurations, the study demonstrates once again how the economic sustainability of projects based on biomass gasifiers is strongly dependent both on the cost of biomass and the current energy market with which it competes. Only extending the use of the charging station to private vehicles generates a return on investment of around 7 years. However, through gasification is possible to achieve carbon capture and storage that, in the analyzed case study, is almost equivalent to the annual CO_{2eq} emission of 4 diesel buses.

1. INTRODUCTION

The most recent EU regulation [1] aims at banning the sale of cars and light commercial vehicles that emit CO_2 starting from 2035 and effectively making only electric vehicles marketable. An electric vehicle, if powered by a battery pack (BEV), can move without emitting CO_2, limiting the production of pollutants to only the particulate matter released during wear of the braking system and wheels. The EU program is particularly ambitious since until a few years ago, excluding the niche of cable transport, the only sector in which a massive and effective use of electric traction was seen was that of rail vehicles, moreover in scenarios limited to Europe and some areas of Asia [2].

However, the situation is changing rapidly. With reference to road vehicles, in particular mopeds, motorcycles, cars and light commercial vehicles, there has been a notable increase in supply from manufacturers followed by a surge in sales, as shown by global market data.

The notable increase in sales was also favored by the incentives allocated by most of the world's governments [3], which can be exploited by private citizens and companies. In reference to the latter, the number of vehicles in circulation that are part of company fleets should not be overlooked: these vehicles can have easy-predictable paths and achieve high annual mileages, translating into equally high emissions saving. In addition to the environmental aspects, converting a fleet to electric can bring other advantages, including lower costs for fueling and maintaining vehicles and an improvement in the company look. In Italy and Europe there are several companies, both public and private, that have carried out or are planning the electrification of their fleet [4]. The experience of using electrified cars in the workplace can also encourage employees to evaluate this choice in the private sector.

As regards heavy electric vehicles for road transport, their market share is still very small, as are the manufacturers' catalogues, although the offer is continually expanding [3]. The main reason is due to the limited range, since even modern battery packs do not reach the energy density necessary to power vehicles requiring high power such as semi-trailers for long motorway journeys.

However, if the area of use is urban, electric vehicles become competitive again, being able to exploit technologies such as generative braking. This is demonstrated by a recent increase in registrations of battery electric buses, especially in China and Europe [3]. A virtuous example in Italy is represented by ATM, the company that manages public transport in the city of Milan, which has a constantly expanding fleet of 167 electric buses [5]. For the recharging and maintenance of the buses, a profound update of the ATM depot in San Donato Milanese was necessary, where various systems were implemented for the refueling of the new vehicles [6].

Modern charging standards require very high-power outputs [7] to fill high-capacity batteries in a short time; therefore, one of the critical issues in fleet conversion lies in being able to supply the necessary energy at the right time.

The main technical characteristics of some of the most representative electric vehicles for each segment are illustrated below.

Looking at Table 1, it is easy to imagine the high energy and electric power availability needs of an entire company fleet, thus demonstrating the need for the creation of an effective dedicated charging infrastructure. The latter can be assimilated to a microgrid, integrating storage systems within it to better manage power peaks, and microgeneration systems to reduce grid connection costs and emissions.

Within the microgrid, there is an opportunity to integrate renewable energy sources, facilitating the transition away from fossil fuels.

The focus of this study is the technical and economic assessment of the integration of biomass generator and battery energy storages systems (BESS) for the creation of high-power charging stations (HPCs) designed to recharge urban buses at night and serve private vehicles during the day.

The wood biomass generator, based on gasification technology, offer sustainable recovery of locally produced prunings from orchards and vineyards for electricity production, while the BESS allows to decouple installed power from the power available to the HPCs.

The electric conversion of urban public transport in the city of Carpi (province of Modena - Italy) was chosen as a case study. The agricultural context in which the city is located is favorable to the study of energy production plants from waste biomass since one of the main crops is wine grapes.

In the next chapters we start from the description of the current context of vineyard pruning usage, the description of the components of the microgrid and of the case study. The evaluation of different microgrid configuration will bring to the definition of pros and cons of the implementation of this technology, bringing among the results an economic assessment to evaluate the sustainability of the proposal. An assessment of the gasification plant's capacity for carbon capture and storage will also be conducted.

Table 1. Characteristics of the main electric vehicles by segment [8, 9]

Segment	Manufacturer	Model	Battery Capacity[1, 2] [kWh]	Max Charging Power[2] [kW]	Range[2] [km]
A	Volkswagen	e-up!	36.8	37	253
B	Peugeot	e-208	50	101	350
D	Tesla	3	78.1	250	629
F	Lucid	Air	120	300	828
N1	Renault	Kangoo E-Tech	48	80	285
N1/N2	Iveco	eDaily	111	80	300
N3	Volvo	FH Electric	542	250	/ [3]
Bus	Solaris	Urbino 9LE Electric	350	240	/ [3]

Note: 1. Nominal values; 2. Values referring to the best performing configuration, autonomy declared by the manufacturer according to the WLTP cycle; 3. Insufficient or insignificant data, as they are too dependent on the conditions of use.

2. MATERIALS AND METHODS

2.1 The current fate of vine prunings

In 2023, Italy once again led global wine production with 42.5 million hectoliters, supported by its 664 thousand hectares of vineyards, including 53 thousand in Emilia-Romagna region [10]. The annual vineyard pruning generates substantial biomass, ranging from 1 to 5 tons per hectare, amounting to 87 thousand tons in Emilia-Romagna region alone [11].

Despite environmental concerns, the adoption of a recovery chain for vineyard prunings, involving baling or chipping and delivery to nearby biomass thermoelectric plants, faces challenges, chiefly the cost linked to proximity [12, 13]. Convincing farmers to opt for this eco-friendly disposal method over open burning remains difficult. Nonetheless, utilizing pruning for energy aims to mitigate agriculture's climate impact, emphasizing its broader environmental significance [14, 15].

The main objective of this work is to explore the feasibility of creating a local supply chain that serves a dual purpose. Firstly, it should reduce the collection basin extension to a few kilometers, secondly, it should enable the on-site production of electricity for the implementation of an urban charging station to recharge private electric vehicles during the day and the city bus fleet during the night.

2.2 Description of the microgrid and the case study

When feasible, implementing a microgrid to support the charging station is preferable to a conventional system directly connected to the national electrical grid. In typical solutions, the load demanded by parked vehicles is immediately absorbed by the macrogrid, leading to several disadvantages [14]: the grid’s contracted power limit hampers the station's absorption capacity, impacting charging speed and point availability. Increasing power is costly and often technically constrained, while power consumption peaks strain the national grid compromising stability.

These issues are addressed in stations supported by a microgrid [16]: energy storage systems mitigate consumption peaks by distributing energy over time, enhancing station output beyond grid limits. The presence of a generator and storage system ensures grid resilience.

In Figure 1, a scheme of the investigated microgrid is shown.

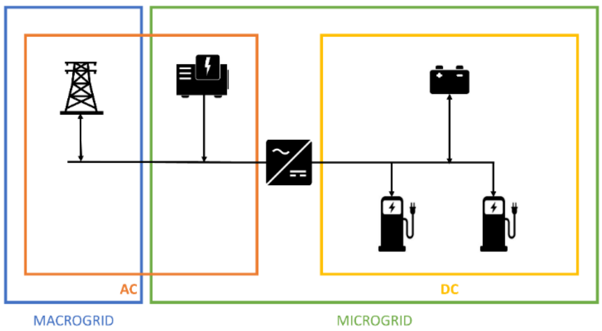

Figure 1. Scheme of the proposed charging station microgrid

2.2.1 Energy sources

In the case investigated, the generator used in the microgrid consists of a generator based on biomass gasification. In its simplest form, a biomass generator consists of a gasification reactor that converts solid biomass into fuel gas (syngas) and the fuel gas is used to power an internal combustion engine which, connected to a generator, generates electricity.

The biomass used is woodchips obtained from vine prunings, with an estimated cost of 50 €/ton [17]. The literature on the use of this biomass in gasification is not very widespread but the authors have carried out several tests on a small-sized Power Pallet 30 gasifier from All Power Labs and these results are transferred to this work [18]. In this regard, the gasifier considers an electrical efficiency (η_{el}) equal to 16.1%, consisting of a biomass specific consumption (ϕ_{bio}) equal to 1.17 kg/kWh$_{el}$. Furthermore, the gasifier generates biochar as a byproduct in the amount of ϕ_{char} =5% of the dry biomass consumption. Biochar is a high carbon content charcoal (60-80%) recognized globally as a carbon storage pathway, making gasification a potentially carbon-negative technology.

It is estimated that each kg of biochar produced is equivalent to approximately 1.8 kg of equivalent CO_2 (CO_{2eq}) calculated through the VERRA methodology [19].

Although the results obtained refer to a very specific gasifier, it was decided to extend their validity to a generic gasifier installed in the microgrid operating with vine chips. The electrical power output of the biomass generator ($\dot{E}_{gas}$) varies linearly according to the state-of-charge (SoC) of the BESS:

- SoC >100%: generator at idle, no power is delivered;
- 100%<SoC<90%: the power supplied by the generator is reduced to 80%;
- 90%<SoC<85%: the power supplied by the generator is reduced to 75%.

The biomass amount required by the gasifier is then calculated according to Eq. (1) while the biochar production through Eq. (2).

$$m_{bio,dry} = E_{gas} \cdot \phi_{bio} \tag{1}$$

where, E_{gas} is the electrical energy generated by the gasifier in a span of time.

$$m_{char} = m_{bio,dry} \cdot \phi_{char} \tag{2}$$

2.2.2 Energy storage

In the microgrid, the electricity drawn by the grid or generated by the gasifier is used to recharge the BESS.

Many existing systems use battery accumulators, which guarantee excellent performance especially in applications where high power is required for frequent cycles. Solutions of this type are also particularly flexible due to their modular structure. The capacity (C_{BESS}), in fact, can range from a few kWh up to hundreds of MWh based on the number of modules installed. The preferred technology is lithium-ion, due to its high energy density. In fact, it is observed that in the United States, as of 2019, 90% of the capacity installed in battery storage systems exploited this technology [20]. The high purchase cost is justified by the high longevity which can exceed 10000 cycles if kept at the correct temperature and used in an appropriately limited charging range.

It is in fact essential to support the cells with a complex management system that takes care of their charging/discharging, health, cooling and safety. Many manufacturers have "all-in-one" solutions in their catalog which contain all the components necessary to carry out these functions within a container. It was therefore decided to adopt this solution in the microgrid under study and select a Power Sonic LiFePO4 modular battery rack [21].

It is through the BESS that electrical energy is delivered to the charging stations, thus decoupling the energy generation power and the delivery power which can therefore be much higher, according to the characteristics of the BESS.

The round-trip efficiency (η_{BESS}) of the BESS equal to 96% was considered.

2.2.3 Charging stations

It is possible to classify the charging station technologies into four levels, based on the power delivered [14]:

Level 1 and 2 stations provide alternating current which is converted into direct current on board the vehicle, limiting the power to 3 kW and 22 kW. The first standard, corresponding to charging from a domestic socket, is more suitable for light vehicles such as scooters, electric bikes and mopeds.

Level 3 and 4 stations instead supply direct current directly, delegating the AC/DC conversion to an external rectifier, larger and adequately cooled. The achievable powers go up to 350kW for the third level and up to over 1MW for the fourth [22], the adoption of which is reserved for large commercial vehicles.

There are also different shape factors of the charging stations, which can be selected according to the space and delivery speed requirements. The market currently offers wall-mounted (wallbox), column and pantograph installations [23].

In this work, it was chosen to install 8 charging columns of 150 kW each. The choice is based on the number of buses in service in the city of Carpi, in the hypothesis of recharging them all in parallel during the night.

The selling price of electricity for the charging of private BEVs has been set at 0.45€. However, this price is cautious for vehicles that can aspire to charging powers of 150 kW.

2.2.4 The case study

The urban public transport system of the city of Carpi is divided into 4 lines of length between 8 and 12 km, each traveled in both directions with a semi-hourly frequency. To guarantee the service, 8 vehicles operating simultaneously are sufficient. Table 2 summarizes the data relating to journeys [24]. The organization of the service provides for an interchange between all lines every half hour, during which the vehicles are reassigned to different lines; in this way it is possible to converge the daily journeys of all buses to the average of 231.4 km.

Table 2. Analysis of the routes of the urban buses of Carpi [24]

Bus Line	Range [km]	Daily Trips	Avg Trip Length [km]	Daily Range [km/day]	Avg Daily Range per Bus [km/day]
Blu	8.1	52	8.9	1851.2	231.4
Red	11.3	52			
Yellow	7.9	52			
Green	8.3	52			

To replace the current 7-8 m long diesel buses, we opted for the Urbino 9 LE Electric model, produced by Solaris. Although this 9-meter version is the smallest manufactured, it is able to accommodate up to 73 passengers of which 27 are seated. The electric motor delivers a maximum power of 220 kW and it is fueled by a lithium-ion battery with a capacity of 352 kWh [9]. For the chosen bus model, a specific consumption of 1.2 kWh/km [25] was considered, for a total daily energy requirement of 277.7 kWh. The battery capacity is sufficient to complete the entire working day without intermediate charging stops, leaving sufficient margin for transfers to the depot (about 10 km per day) and any additional consumption of the HVAC system on particularly hot or cold days.

2.3 Determination of charging profiles for light vehicles and buses

In order to simulate the vehicular traffic on the road where the recharging station is installed, the Monte Carlo method was used [26]. In this regard, the following variables were evaluated:

• Vehicular flow intensity: the data collected by ARERA [16] for the Italian scenario shows that, on average, ultrafast charging stations are used for 10-12% from 00am to 8am, 53-55% from 8am to 16pm, 33-36% from 16pm to 00pm. Since there is great uncertainty both about the location of the bus depot where the charging station could potentially be installed, and about the vehicular traffic that could be present, a normal distribution of the probability of passing vehicles was considered, divided into three daily ranges with the following characteristics:

Range 1: Average at 8am with a standard deviation of 40 minutes;

Range 2: Average centered at 13am with a standard deviation of 2 hours;

Range 3: Average centered at 6 pm with a standard deviation of 40 minutes.

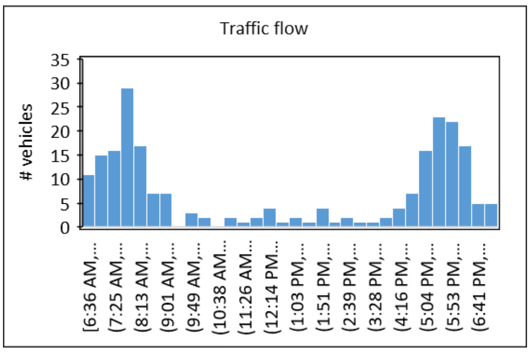

Figure 2. An example of the daily trend of the traffic flow generated by the model

In the three ranges, the total passage of up to 100, 50 and 100 vehicles were considered respectively. Figure 2 shows one of the possible vehicle flow charts generated in the model.

• Vehicle type: 4 different types of vehicles were considered, the occurrence of which was calculated randomly and whose data are shown in Table 3.

• Vehicle SoC: for each vehicle that approaches the charging station, a different SoC between 20% and 40% was considered. The SoC leaving the charging station is considered as a random variable between 80% and 90%. A minimum stop time of 15 minutes has been chosen: if the vehicle requires less than 15 minutes it does not stop to recharge. The recharge power is defined by the minimum value between the max charging power of the specific vehicle and the maximum power that can be supplied by the station (150 kW).

Table 3. characteristics of the BEV considered in this work

Car Model	Consumption WLTP [km/kWh]	Range [km]	Charging Power [kW]	Battery Capacity [kWh]
1	7.1	533	250	75
2	6.4	362	100	50
3	4.9	270	50	40
4	7.2	227	35	26.8

The charging station is open to the public from 6am to 7.30pm five days a week for 52 weeks, while bus charging takes place from 8pm to 5.30am.

It is considered to recharge the buses in parallel at a constant power of 29.3 kW in order to reach full charge in the 9.5 hours available at night.

2.4 Scenario analysis

2.4.1 Model description

The load generation and simulation model of the microgrid with connection to the electricity grid was built using Visual Basic using Excel macros.

In this first version of the model, the gasifier always recharges the BESS, which provides the high-power discharge towards the HPCs. When the expected SoC of the battery is <0 then the electrical energy is taken from the grid, supplied to the battery and discharged to the HPCs. The round-trip efficiency of the BESS is accounted for whenever there is an energy withdrawal, at that moment also counting the charging efficiency of the BESS itself and of the AC/DC converter (Eq. (3)).

$$E_{BESS} = (E_{gas} + E_{grid})\eta_{BESS} = E_{load} \quad (3)$$

Different scenarios were therefore analysed, differentiating by the size of the different components and according to the following code A_B_C where A represents the power installed through the biomass generator, B indicates the electrical capacity of the BESS while C indicates the electrical power used by the national grid.

2.4.2 Economic analysis

The economic viability assessment relies on investment costs, variable expenses linked to power generation system operation and maintenance, electricity consumption potentially drawn from the grid, and revenues generated from selling energy to motorists and from reduced diesel usage in bus transportation. Inflation rates affecting electricity costs were set at 5%. The specific cost of the power generation system is assumed to be 3250 €/kW, with annual maintenance costs estimated at 80 €/MWh, based on findings from Wei et al. [27] for a small-scale gasifier. The BESS investment cost is estimated at 450 €/kWh [28]. Additionally, revenue from selling biochar was factored in with a selling price estimated at 300 €/t (as per producer quotation).

An evaluation was carried out on the Net Present Value (NPV), taking into account the costs, savings, and revenue produced through the utilization of the gasifier as an energy source. A discount rate of the 6% was considered in this analysis [29].

The expected cost of electricity was varied depending on the electrical power required from the national grid. This is made up of a fixed quota, a quota dependent on the price of energy and a quota determined by the electrical power requested [16].

For each tested configuration, the cost of connection to the national network was then determined following Eq. (4).

$$e_{grid} = x + y \cdot \dot{E}_{av} + z \cdot E_{tot} \tag{4}$$

where, e_{grid} is the electricity price for the energy drawn from the electrical grid, $\dot{E}_{av}$ is the available power from the grid connection and E_{tot} is the total energy drawn from the grid on a certain time span. Parameters *x*, *y* and *z* are reported in Table 4.

In the next section the results on the impact that different parameters have on the payback time are reported.

Table 4. Parameters for calculating the annual electricity tariff

$\dot{E}_{av}$ [kW]	*x* [€/y]	*y* [€/(kW y)]	*z* [€/kWh]
>33	50.72	59.98	0.0560
<100	1381.09	66.88	0.0540
≤500	1291.10	60.06	0.0539
>500	1263.71	52.69	0.0538

3. RESULTS

The distribution profile of vehicular traffic has repercussions on uneven load demand between the different charging columns (HPC_1 to 8). Figure 3 shows an example of the annual energy demand required by each column. The shape of the profile is determined by the logic implemented in the model which tends to favor the columns in order of number.

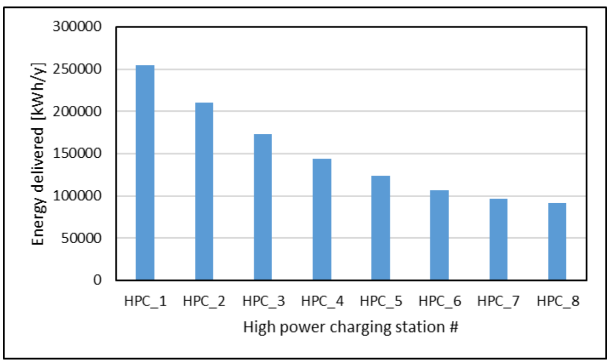

Figure 3. An example of the energy withdrawn from each HPC

The load profile was then implemented in the model for simulating the operation of the microgrid connected to the electricity grid.

Eight different microgrid configurations were tested, varying the power installed on the electricity grid and gasifier and varying the capacity of the electrical storage.

Figure 4 shows the cash flows obtained from the analysis of the different scenarios together with the carbon storage obtained from the production of biochar. It is observed that the highest cash flow occurs in the absence of investments in the creation of the microgrid. The high costs of the gasification plant linked to the cost of biomass and operation and maintenance (O&M) in fact exceed the cost of the power quota for the request of 1.2 MW in the case of absence of the microgrid (configuration *0_0_1200*). As regards the other solutions tested, a reduced cashflow is observed both in the cases without electrical energy drawn from the grid, and in the *300_150_300* case with small BESS and power available from the grid equal to 300 kW. The reasons are of different nature: in the case of only a gasifier present, the available power (gasifier + BESS) is not always sufficient to satisfy the energy demand from the columns, causing a loss of customers. In the case of a hybrid microgrid-macrogrid connection, however, the fixed costs linked to the electricity connection increase annual expenses, reducing cash flow.

In terms of CCS, small variations are observed in cases where the gasifier is present and are also linked to the ability to satisfy 100% of customers who require recharging.

It should also be noted that variations in the order of 5% can be attributed to the variability of vehicular traffic entering the HPCs.

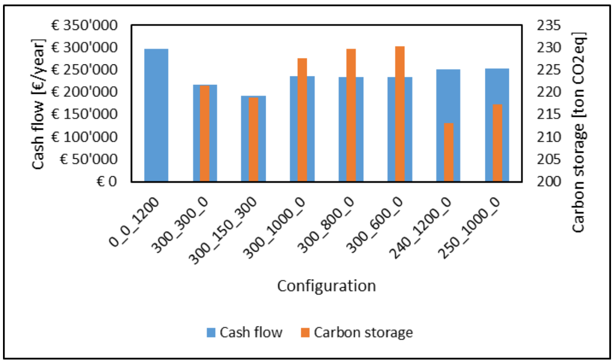

Figure 4. Cash flow analysis and carbon storage for each tested configuration

The average carbon storage capability was estimated at 223 tons of CO_{2eq} per year, which roughly equates to the carbon footprint of 4 diesel-powered urban buses operating in the city of Carpi.

The estimate of the payback period is shown in Figure 5 where payback times between 6.3 and 7.7 years are reported and it can be noted that they are more affected by the size of the gasifier rather than the BESS capacity.

Figure 6 shows the NPV trend for the case with a 250 kW and 1000 kWh BESS gasifier installed while Figure 7 shows, for the same case, the example of a weekly trend of the charge/discharge profile of the BESS and the power delivered by the gasifier. We observe what was anticipated in the previous paragraph, i.e. the zeroing of the capacity of the BESS in certain periods of the day (mainly during the morning rush hour) which leads to a loss of customers. It can also be observed the achievement of full capacity of the BESS in the central part of the day which determines a reduction in the load of the gasifier.

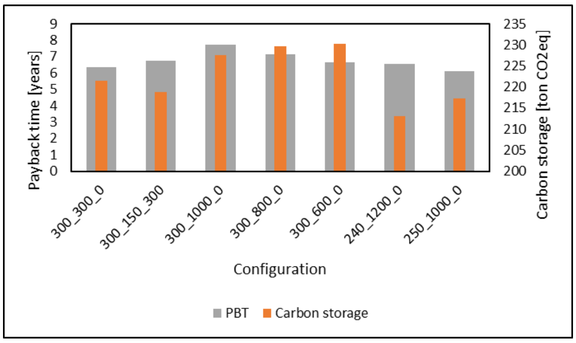

Figure 5. Payback time and carbon storage for each tested configuration

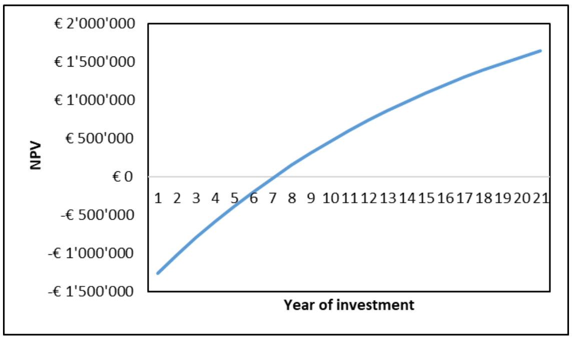

Figure 6. NPV analysis of the case *250_1000_0*

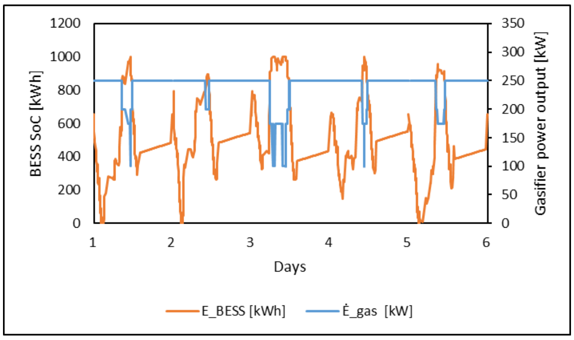

Figure 7. One-week analysis of the gasifier load profile and BESS SoC

Figure 8. Land use map within a 6 km radius centered on the biomass power plant. Vineyard plots are marked in red [30]

The average biomass consumption, calculated between the different configurations tested, is around 2400 ton/y of dry biomass. In the absence of precise data on the viticultural crops in the area around the city of Carpi, the average amount of annual pruning production was taken as the one measured by Toscano et al. [17] that is 2.31 tons/(ha y) with moisture content equal to 50%wb. It should be noted that this data is extremely variable depending on the variety of vine and the type of viticultural system.

Through this average data and the land use maps available in GIS format on the Emilia-Romagna region portal [30], it was possible to estimate the collection basin for the necessary biomass which extends just over 2000 hectares and is equal to 6 km collection radius centered on the biomass power plant (Figure 8).

4. CONCLUSIONS

In this study, the utilization of gasification technology was tested in a relatively unexplored area, namely, generating electricity to power a charging station available for private BEV during the day and for recharging electric urban buses at night. The investigation was focused on the case study of the city of Carpi, where it was observed that the construction of a microgrid faces challenges in competing with the (currently again contained) costs of electricity from the national grid. Constructing a microgrid may prove advantageous in cases where reducing reliance on the grid is desired while still ensuring high power for charging stations to provide a well-compensated service. In this scenario, employing a biomass generator for electricity production coupled with a BESS appears to be a costly choice, with a payback period of 6-7 years depending on the scenario considered. Beyond the purely economic aspect, it's crucial to highlight that gasification enables carbon capture and storage, quantified by a CO_{2eq} saving of around 220 tons per year, equivalent to emissions from about 4 urban diesel-powered buses. Finally, it is noted that the collection area for agricultural biomass, from vineyard prunings, can be found within a 6 km radius. This highlights a second aspect: although the collection radius is small, it would only cover a minimal portion of what could be the city's electricity consumption for vehicle charging in a near future. This raises both new and old questions about available local resources and confirms (if there were any doubts) that residual biomass can only be a small part of the solution.

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NOMENCLATURE

E	Electrical energy, kWh
$\dot{E}$	Electrical power, kW
m	Mass, kg
SoC	State of charge
BEV	Battery electric vehicle
C	Battery capacity

Greek symbols

η	Efficiency
ϕ	Specific consumption/production

Subscripts

gas	Gasifier
bio	Biomass
char	Biochar
BESS	Battery energy storage
grid	National electricity grid
load	Electrical load from vehicle/bus charging demand
wb	Wet basis