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# Sustainable Energy Paths: Harnessing Residual Biomass Potential in Southern Italy

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**ABSTRACT**

The rising demand for biomass for energy production presents several critical issues, including competition for land use, deforestation, the decision between using crops for food or biofuels, the use of food resources, and the impact on water systems. One potential solution to address these issues is the utilization of residual biomass for energy generation. This, together with the advantage of replacing dedicated biomass, allows reducing greenhouse gas emissions and related climate change issues connected to residues decomposition that occurs when these substrates are landfilled or not properly collected and treated. To assess the contribution of residual biomass on the energy mix at a local, regional or national scale, estimating the potential of this resource is fundamental. Therefore, in this work, the availability of residual biomass from agriculture, including animal manure and vegetal residues such as those from arable field crops and horticultural plants, which are mainly straw, stalk, husk, stem-leaf, pruning, is considered. The physicochemical characteristics of residues as well as the geographical distribution of crops and livestock is considered. The analysis is carried out for a Southern Italy region, by using statistical and literature data. Then, for the same region the effect of using this untapped resource on the reference energy mix as well as on some scenarios previously developed for improving its decarbonisation is assessed.

## 1. INTRODUCTION

Biomass is primarily used to generate electricity and heat through advanced combustion and co-firing technologies, utilizing wood, agricultural residues, and municipal solid waste [1, 2]. It is also processed into biofuels like ethanol, biodiesel, and bio-oil, which are considered sustainable alternatives to fossil fuels, with biofuels from lignocellulosic materials such as wood and agricultural waste showing great promise due to their abundance and affordability [3]. Additionally, anaerobic digestion of biomass produces biogas, which serves as a renewable energy source for heating, electricity, and vehicle fuel, while managing organic waste and reducing greenhouse gas emissions [4]. Biomass is also used in combined heat and power (CHP) systems that enhance energy use efficiency by generating both heat and electricity, often in industrial settings using waste biomass [5]. Finally, biomass pellets, made from compressed organic matter like sawdust and crop waste, are used in residential and commercial heating systems due to their compactness and high energy density [6].

Among the different available biomasses, agriculture residues represent a promising source for bioenergy production. Moreover, recovering this biomass allows on one hand to reduce the great effort, capital, and labor connected to its management, on the other hand to face the issues related to its improper management that can lead to environmental damage, such as groundwater contamination from nitrate leaching, heavy metal contamination, and other ecological nuisances [7]. According to FAO data [8], the agrifood sector produces one-third of total anthropogenic GHG emissions, with the highest contribution, almost half of the total (7.4 Gt $CO_{2eq}$), due to crop and livestock production activities, followed by pre- and post-production (5.6 Gt $CO_{2eq}$) and land-use change (3.1 Gt $CO_{2eq}$). Almost 20% of emissions related to crop and livestock production activities are caused by livestock manure, whose improper management is particularly problematic for the environment due to the high release of methane that is a much more potent greenhouse gas than carbon dioxide [9].

Finally, it is worth noticing that utilizing residual biomass for energy not only helps in reducing greenhouse gas emissions but also supports habitat preservation and biodiversity by promoting proper vegetation management [10].

Due to the high contribution that energy recovery of agriculture residues may have on decarbonization at local level, the present work presents:

- an estimation of bioenergy potential of the agriculture sector at regional level, by considering Campania region, Southern Italy, as case study;
- the implementation of the estimated bioenergy potential in the energy mix of Campania region, to propose different future energy scenarios with reduced emissions compared to the current situation.

## 2. METHODOLOGY

### 2.1 Methodology framework

This paper builds upon previous research on energy strategy implementation, focusing on a regional energy system and envisioning a scenario for the year 2050 [11]. The objective was to achieve an 80% reduction in $CO_2$ emissions compared to 1990 levels, aligning with European environmental targets for that year. For clarity, a concise description of the methodology is provided, with more details available in study by Battaglia et al. [11].

The study provided a framework for effectively integrating local resources and energy efficiency measures, analyzing national objective achievement, burden sharing, and the 'smartness' level of the regional system.

The proposed methodology enabled not only the simulation of future scenarios using a smart energy system approach but also incorporated site-specific renewable energy source (RES) potentials in the hourly analysis, assessing flexibility.

The actual regional energy system model was developed by evaluating energy consumption and production for a base year (2017) across various sectors (electricity, heating, cooling, industry, and transport). This was achieved through a detailed bottom-up approach using Geographic Information Systems (GIS) and energy simulation tools, conducted on an hourly basis.

The overall system architecture was designed using the main techno-economic model, EnergyPLAN [12].

Building on the baseline energy system model, an enhanced integration of RES was undertaken. The sustainability of the system was assessed based on energy consumption, emissions, and cost metrics.

2.1.1 Baseline scenario modelling

The energy system under analysis is based in Campania, a densely populated area in Southern Italy. To develop the energy model, it was necessary to gather and process the relevant input data before reconstructing the system within the 'EnergyPLAN' framework.

The EnergyPLAN model is preferred for its ability to integrate extensive technological changes and its compatibility with site-specific conditions, offering flexibility in input data and compatibility with other tools and it is capable of high-resolution timing to handle fluctuations in renewable energy sources and demands. It has been effectively used for energy system modeling across various scales from cities to nations, focusing on parameters like energy demands, technology efficiencies, and environmental impacts [13].

The study on energy consumption and production in Italy utilizes data from national databases and TERNA [14] to analyze annual and hourly electric energy consumption. Heating and cooling demands are estimated using degree hours methods based on plant operations.

Domestic hot water usage and road transport impacts are modeled through dynamic simulation tools and emissions data, respectively. Industrial data encompasses company counts, employment, and fuel consumption at a regional level.

For energy supply, data on installed capacities of both renewable and traditional power sources is accessed via Atlaimpianti [15], with energy production from photovoltaic plants and solar collectors simulated using TRNSYS software [16].

To compare the model to the actual balance, the key numbers used for validation are: 1) Electric energy demand and supply; 2) $CO_2$ emissions; 3) Fuel balance.

2.1.2 Future scenario implementation

To address the environmental challenges, future scenarios for 2030 and 2050 were created for Campania, aiming to reduce emissions by 40% and 80% respectively, compared to 1990 levels, based on the integration of RES and sector coupling.

The future scenarios for Campania's energy system are based on several key assumptions, including the electrification of the transport sector with electric and hybrid vehicles utilizing vehicle-to-grid technology, the regional expansion of wind and solar energy, and the introduction of district heating and cooling systems in areas with high geothermal potential and heat demand. The 2050 scenario builds on the 2030 model, with further electrification of transport, unchanged thermoelectric generation levels, and district heating systems powered by combined heat and power plants fueled by natural gas and renewable sources. It also includes increased installations of wind and photovoltaic systems and the exploitation of biomethane.

Finally, to improve system self-sufficiency and environmental impact, the 2050 scenario introduces the use of biomass.

### 2.2 Integrating RES into future energy scenarios

The development of future energy systems typically revolves around integrating renewable energy sources (RES) and enhancing energy efficiency. The limitations to expanding renewable capacity generally fall into two categories: 1) The technical potential related to the geographic area; 2) The physical space available for installations. For each renewable technology evaluated, these constraints were considered. The first constraint was explored through bibliographic research, while the second was assessed using GIS software tools [17]. Once these constraints were established, it became possible to determine whether the maximum feasible installation capacity was adequate to meet the set targets and how these installations could be optimized within the system for best performance.

2.2.1 Biomass potential evaluation

Energy potential from residual biomass is calculated by employing statistical information and literature data, with a specific focus on the main products of the Campania region. More in detail, different crops are considered. The estimated primary energy potential of the j-th residue of the i-th vegetal biomass, $EPVB_{i,j}$ is calculated as shown in Eq. (1):

$$EPVB_{i,j} = P_i \cdot RtP_{i,j} \cdot (1 - MC_{i,j}) \cdot LHV_{i,j} \cdot A_{i,j} \tag{1}$$

where, $P_i$ is the production of the i-esim crop, $RtP_{i,j}$ is the residue-to-product rate of the j-esim residue of the i-esim vegetal biomass, respectively, $MC_{i,j}$ is the moisture content of the j-esim residue of the i-esim vegetal biomass, $LHV_{i,j}$ is the lower heating value of the j-esim residue of the i-esim vegetal biomass and $A_{i,j}$ represents the residue availability factor.

Farming is another important sector of agriculture in Campiania region. In this case the main residue is represented by manure, whose energy content is commonly recovered by producing biogas or biomethane through the biological process of anaerobic digestion. Thus, the estimated primary energy potential of the residues of the i-th livestock $EPAB_i$, may be calculated as shown in Eq. (2):

$$EPAB_i = L_i \cdot M_i \cdot 365 \cdot Meth_i \cdot LHV \cdot A_i \quad (2)$$

where, $L_i$ represents the population of the i-esim livestock, $M_i$ is the daily manure yield of the i-esim livestock, $Meth_i$ is the specific methane yield of the manure produced by the i-esim livestock, LHV is the lower heating value of methane, and $A_i$ represents the residue availability factor. $Meth_i$ is derived from literature.

For both vegetal and animal residues, the availability factor is considered. This coefficient is considered to estimate the residues that are technically recoverable, by excluding the losses due to transformation, collection, transportation, handling and storing of residues as well as the fraction that is commonly employed for reuse, i.e. as fertilizers, forage, or industrial raw materials.

The values employed to estimate the energy potential available from residual biomass of vegetal and animal origin are reported in Table 1 and Table 2, respectively.

Data about crop production and livestock are collected from the information reported by the Italian national agency of statistics for the year 2022, whereas the other parameters are derived from the literature.

**Table 1.** Coefficients used to assess the residue production and the energy potential of the vegetal sector [18]

| | RtP ($kg_{residue}/kg_{product}$) | MC (%) | LHV (MJ/kg) | A (%) |
|---|---|---|---|---|
| Almond | 1.9 | 25 | 18 | 95 |
| Hazel | 1.9 | 40 | 18.7 | 95 |
| Citrus | 0.4 | 40 | 18 | 95 |
| Peach | 0.2 | 40 | 18 | 95 |
| Apricot | 0.1 | 40 | 18 | 95 |
| Plum | 0.1 | 40 | 18 | 95 |
| Apple | 0.1 | 40 | 18 | 95 |
| Pear | 0.1 | 40 | 18 | 95 |
| Cherry | 0.1 | 40 | 18 | 95 |
| Kiwi | 0.2 | 40 | 18 | 95 |
| Olive | 1.14 | 45 | 18 | 90 |
| Vine | 0.39 | 45 | 18 | 95 |
| Wheat | 1.09 | 13.8 | 16.1 | 51.6 |
| Barley | 1.1 | 14.1 | 17 | 51.6 |
| Oat | 1.33 | 13.3 | 17.1 | 43.7 |
| Rye | 1.79 | 13.5 | 17.5 | 43.7 |
| Maize | 1.2 | 50 | 15 | 35 |
| Sunflower | 2 | 36 | 14.9 | 68.3 |
| Rapeseed | 1.73 | 41.7 | 15 | 55 |
| Legume | 1.63 | 15 | 16 | 65 |
| Potato | 0.56 | 34 | 15 | 69 |

**Table 2.** Coefficients used to assess the residue production and the energy potential of the animal sector [18]

| | M ($kg_{manure}$/(Head of Livestock d)) | A (%) | Meth ($m^3_{CH4}/t_{manure}$) |
|---|---|---|---|
| Bovine and buffalo | 29.6 | 48.3 | 31.6 |
| Poultry | 0.0705 | 85 | 65.3 |
| Sheep and goat | 1.59 | 43 | 23.6 |
| Swine | 3.76 | 65 | 33.6 |

## 3. RESULTS

### 3.1 Energy potential of residual biomass in Campania region

By applying the method described in Section 2.1.1, the primary energy available from the agricultural residues in Campania region is calculated. For the vegetal sector a yearly production of 10.3 PJ/y is estimated, whereas animal manure could produce 80 172 373 $m^3$/y of methane, corresponding to 2.75 PJ/y. For the vegetal sector the data about crops production is available at a province level.

The results obtained are shown in Figure 1, where the crops are assembled in macro-categories, except for olives and vine dedicated to wine production, to highlight their significant contribution.

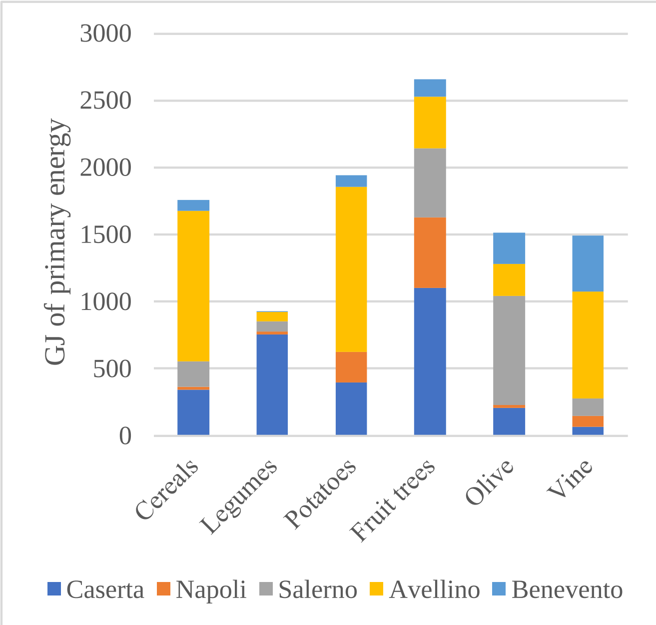


**Figure 1.** Energy potential of the vegetal sector

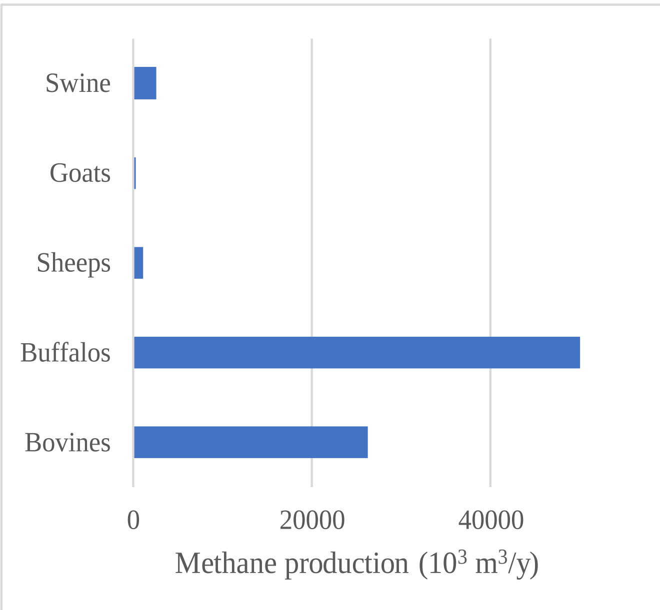


**Figure 2.** Energy potential of the animal sector

The results show that Caserta emerges as one of the most important provinces in terms of primary energy produced by various crops, followed by Avellino. Fruit trees represent the largest source of primary energy, with Avellino and Salerno dominating in this category.

Finally, it can be noticed that there is significant variability between provinces regarding the crops providing more energy, likely reflecting the available surface, the geographical characteristics, the urbanization as well as climatic and agricultural differences within the region.

For the residues coming from the farming sector the data are available only at a regional level. The obtained results are shown in Figure 2.

The results highlight that residue coming from buffaloes' residues are the highest source of methane in Campania region, followed by those of bovines. Production of methane from swine manure is considerably lower, though still notable, whereas it is minimal from goats and sheep.

### 3.2 Current energy mix in Campania

Campania's energy system shows a lack of connection between transport, heat, and electricity demands, with fossil fuels being the primary energy source (Figure 3).

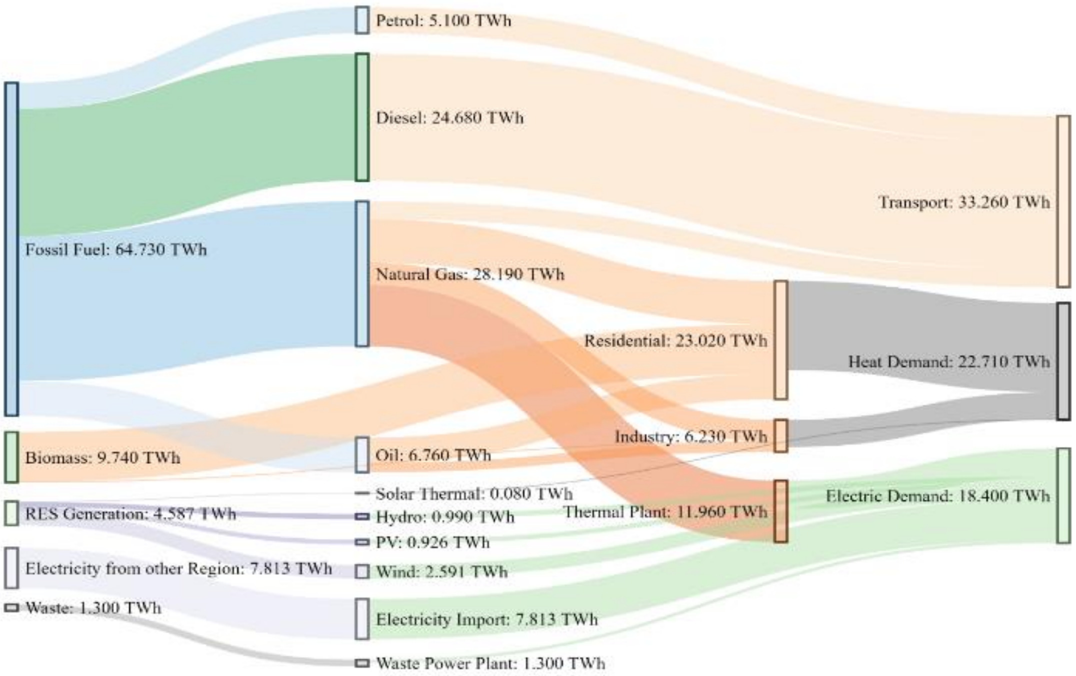


**Figure 3.** Campania energy mix for the base year

This indicates a lack of flexibility in the current energy system, as demonstrated in studies [19, 20]. An increase in renewable energy production could result in Critical Excess Production of Electricity (CEEP), where electricity generation surpasses consumption and system interconnection capacity, potentially leading to system collapse and increased production costs.

Heating demand, primarily met by natural gas, biomass, and oil, totals 22.71 $TWh_{th}$. Despite Campania's high geothermal potential, its use is minimal. Cooling electricity, usually a minor part of the total energy in European regions, accounts for about 10% of Campania's heating budget (approximately 2.11 TWhe) and is projected to rise to 30-70% by 2050 due to improved living standards and climate change effects.

Electricity production in Campania is mainly from:

-Conventional thermal power plants (approximately 62.7%)

-Wind (approximately 23.3%)

-Hydroelectric (5.6%)

-Photovoltaic (8.3%)

In the last 15 years, renewable energy sources (RES), especially wind energy, have become significant. By 2017, Campania had 593 wind turbines with a capacity of 1388 MWe, and other RES capacities included 784 MWe from photovoltaics, 233 MWe from bioenergy, and 337 MWe from hydro plants. In total, Campania had 31,056 RES power generation plants with a combined capacity of 2,741 MWe, producing 4,578 TWhe of electricity.

In 2017, Campania's RES power capacity represented about 5% of the national capacity, making it the eighth Italian region for renewable energy production, contributing nearly 28% of the total production in Southern Italy and the islands (7 Mtep).

### 3.3 Future scenarios

The 2030 scenario includes:

- Electrification of transport, through a shift to electric and hybrid vehicles with vehicle-to-grid (V2G) technology;
- Renewable energy expansion, through an increase in wind and solar energy as per regional plans;
- District Heating and Cooling (DHC), with the introduction in select areas using geothermal energy.

The 2050 scenario builds on 2030 with:

- Increased transport electrification;
- Stable thermoelectric generation;
- Advanced DHC systems, powered by CHP plants using natural gas and renewable energy (geothermal, solar thermal, biomass);
- More wind and PV installations.

Additionally, biomass utilization within the region, as assessed in earlier sections, was integrated into the energy system. Biogas produced from animal manure was intended for incorporation into the gas grid, while agricultural residues were to be gasified to generate syngas, which would also be blended into the gas grid.

3.3.1 Scenarios' results

The demand for electric energy increases from 18.4 TWh/year in 2017 to 26.4 TWh/year in 2050, with significant growth in production from renewable sources, especially solar and wind (Figure 4). Natural gas use in power sector remains a key component until 2030, but its consumption drastically decreases by 2050, while the use of biomass and waste increases substantially.

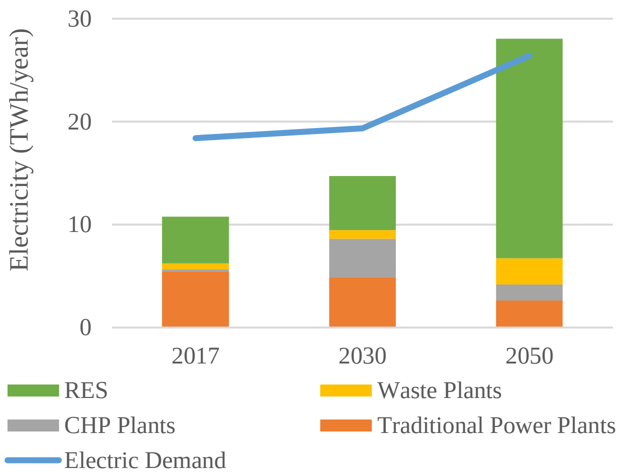


**Figure 4.** Demand and electricity production for type of plant of each scenario

The demand for heating decreases, with a strong shift towards district heating, which covers 76% of the demand by 2050 (Figure 5). The demand for cooling also increases, with district cooling covering 68% of the demand by 2050 (Figure 6). Individual consumption of natural gas and biomass for heating decreases, while solar thermal increases slightly. The consumption of electricity for individual cooling significantly decreases by 2050.

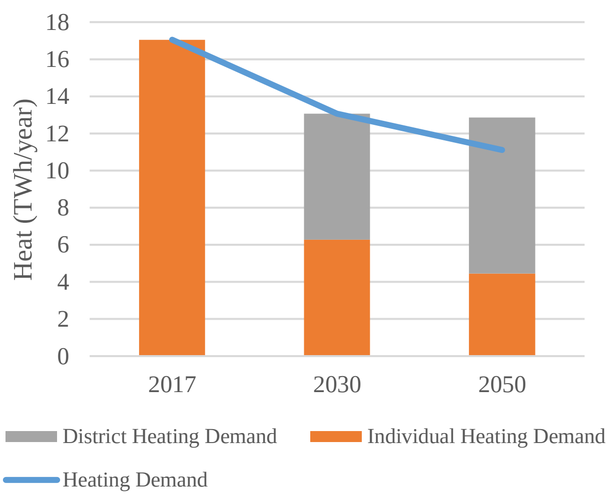


**Figure 5.** Demand and electricity production for type of plant of each scenario

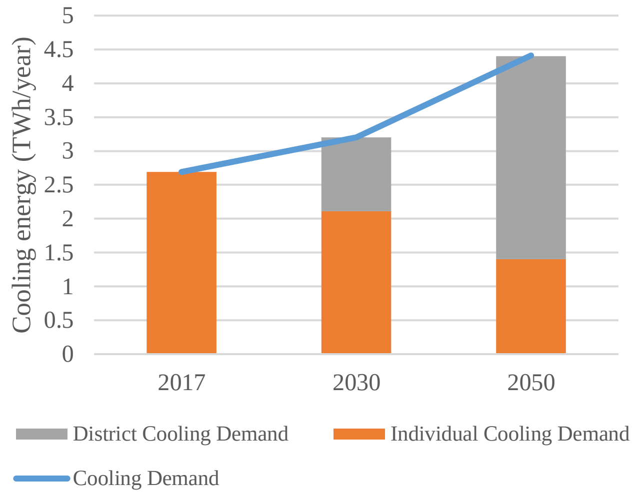


**Figure 6.** District cooling demand for each scenario

In the industrial and transport sectors, the consumption of fossil fuels decreases, shifting towards natural gas and electricity. The use of electricity in transport grows, especially for smart charging.

$CO_2$ emissions reduce by almost 70% by 2050 compared to 1990 levels, with the most significant reduction coming from decreased oil use and a shift to renewable sources and waste (Figure 7).

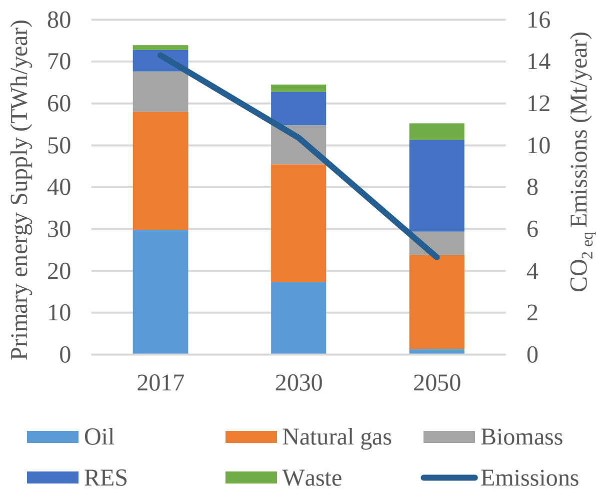


**Figure 7.** Primary energy supply for type of source and $CO_{2eq}$ emissions for each scenario

3.3.2 Decarbonization potential of residual biomass

This section discusses the decarbonization potential of integrating residual biomass into the Campania region's energy system by 2050. The analysis shows that incorporating biomass can substantially increase the share of renewable energy sources, enhancing the sustainability of the energy mix and reducing greenhouse gas emissions. Specifically, the use of biomass boosts the renewable energy share to 87% (Table 3 and Table 4), significantly lowering the region's dependence on natural gas. The findings indicate a potential 72% reduction in $CO_2$ emissions compared to the baseline year, underscoring the role of biomass in achieving climate targets (Figure 8).

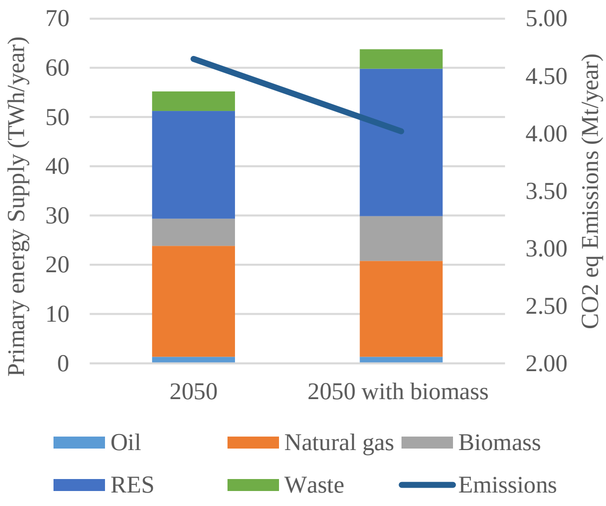


**Figure 8.** Primary energy supply for type of source and $CO_{2eq}$ emissions for each 2050 scenario

Biomass's contribution to combined heat and power plants is notable, offering a versatile solution that provides both electricity and heat, thus enhancing overall energy efficiency.

The implications for policy and practice are clear: developing biomass infrastructure and technology should be prioritized, with incentives for effective residue management and biomass supply. Investments in biomass conversion technologies are essential to realize the benefits outlined in the study. However, challenges such as sustainable biomass sourcing and logistical barriers need to be addressed through continued research and development.

**Table 3.** Fuel balance for 2050 scenario

| 2050 Scenario | | | | |
|---|---|---|---|---|
| **FUEL BALANCE (TWh/year)** | **CHP** | **Traditional Power Plants** | **Waste** | **Total** |
| **Coal** | - | - | - | 0 |
| **Oil** | - | - | - | 0 |
| **N.Gas** | 3.37 | 4.41 | - | 7.78 |
| **Biomass** | - | 1.32 | 3.95 | 5.27 |
| **Intermittent Renewable** | - | - | - | 21.31 |
| **RES Share of PES** | | | | 77% |
| **Emissions Reduction with Respect to Baseline Year** | | | | 67% |

**Table 4.** Fuel balance for 2050 scenario with the use of regional biomass

| 2050 Scenario with Biomass | | | | |
|---|---|---|---|---|
| **FUEL BALANCE (TWh/year)** | **CHP** | **Traditional Power Plants** | **Waste** | **Total** |
| **Oil** | - | - | - | 0 |
| **N.Gas** | 0.28 | 4.41 | - | 4.69 |
| **Biomass** | 3.66 | 1.32 | 3.95 | 8.93 |
| **Renewable** | - | - | - | 21.31 |
| **RES Share of PES** | | | | 87% |
| **Emissions Reduction with Respect to Baseline Year** | | | | 72% |

## 4. CONCLUSIONS

The study explored the potential of utilizing residual biomass for energy production in the Campania region of Southern Italy, highlighting its significant energy potential. Agricultural residues and animal manure were identified as key sources, with an annual energy production estimate of 10.3 PJ/y and 2.75 PJ/y, respectively. The provinces of Caserta and Avellino emerged as major contributors, especially in fruit tree cultivation.

The research emphasized the environmental benefits of using residual biomass, which can substantially reduce greenhouse gas emissions and support biodiversity and habitat preservation. Future energy scenarios for 2050 indicated a significant shift towards renewable energy sources, with biomass playing a critical role in reducing the reliance on fossil fuels. By integrating biomass, the renewable energy share of the primary energy supply could reach 87%, leading to a 72% reduction in emissions compared to baseline levels.

The study utilized the EnergyPLAN model to simulate and optimize future energy scenarios, incorporating site-specific renewable energy potentials and addressing energy system flexibility. Despite technical and physical constraints, the potential for integrating residual biomass presents significant opportunities for sustainable energy development and improved regional energy security.

Future research should focus on advanced integration techniques, policy and economic analysis, regional adaptation studies, and sustainable agricultural practices to maximize biomass residue availability without compromising food security and environmental health. Overall, the findings underscore the importance of integrating renewable energy sources into regional energy strategies to create resilient and sustainable energy systems for the future.

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## NOMENCLATURE

| | |
|---|---|
| A | Availability coefficient, nondimensional |
| EPAB | Primary energy potential of the animal sector, J/y |
| EPVB | Primary energy potential of the vegetal sector, J/y |
| L | Livestock |
| LHV | Lower heating value, J/kg or J/m$^3$ |
| M· | Daily manure yield, kg/(livestock·d) |
| MC | Moisture content, nondimensional |
| Meth | Specific methane yield of the manure, $m^3_{CH4}/t_{manure}$ |
| P | Yearly crop production, kg/y |

**Subscripts**

| | |
|---|---|
| i | i-esim biomass |
| j | j-esim residue |