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Towards a Power Production from 100% Renewables: The Italian Case Study

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Abstract: The need to reduce greenhouse gas emissions is driving many actions to decarbonize the most impactful sectors. Among these, the energy sector accounts for almost one third of emissions. Increasing the penetration of renewable energy in the energy mix could easily reduce the emissions of this sector. Theoretically, the target to aim for would be 100% renewable energy production. However, the variable nature of power production from photovoltaic and wind systems, which are expected to play a key role in the energy transition, may pose several limitations to the effective penetration of renewable energy. Many concerns arise when one considers the large diffusion of renewable energy that would be required to meet green targets, and the operating conditions of other systems in charge of compensating for renewable energy variations. This study aims to investigate the potential impact of an increase in the amount of renewable energy installed in a country, particularly in Italy. A simplified approach has been used, based on the assumption of knowing the hourly demand and power generation mix, and multiplying the intermittent power generation by a certain factor. Although not accurate, this approach allows the authors to highlight some critical aspects regarding the potential surplus of renewable energy and the operating conditions of other energy sources. The results of this study may provide a useful basis for a preliminary system evaluation, in particular to assess the feasibility of surplus recovery and the operability of residual generation systems. In addition, it may be easily replicated in other countries for similar estimations.

Keywords: renewable energy integration; energy surplus; energy storage; power to X

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1. Introduction

In Italy, renewable energy sources (RES) penetration in electricity generation has grown from 16% to 34% in last two decades [1]. Hydroelectric remains the biggest renewable source but wind and photovoltaic (PV) have grown to second and third position, respectively. On 21 January 2020, the Italian Ministry of Economic Development published the text of the Integrated National Energy and Climate Plan 2030 (PNIEC) which is the fundamental act to change the national environmental policy towards decarbonization. The Plan is structured in five lines of action, which will be developed in an integrated way [2]. The PNIEC in its annexes also estimates the evolution of renewable energy systems in the period 2021–2030 with the targets in all energy sectors: 55% share of renewables in the power generation, 33.9% in the heating/cooling of buildings and 22% with regard to transportation. To achieve that ambitious goal of RES penetration in electricity, PV and wind generation capacity must be strongly incremented while for other RES sources only small improvements are expected. In 2030 PV and wind generation have to increase three and two times, respectively, in comparison with 2019 [3].

Many studies dealt with the effects of similar changes in electricity generation but every country in the world has different characteristics in terms of national electrical system peculiarity and RES potential. Italy is representative of a medium sized country with some existing RES electricity generation (hydroelectric, geothermal, biomass), integrated in the last two decades, with remarkable installation of wind and PV, with a good potential of additional capacity. Lund studied the combinations of RES sources in Denmark [4] while Gomez et al. analyzed the Spanish electrical system focusing on the key role of residual traditional generation [5] and the strong differences between a scenario with 90% RES penetration and a 100% one [6]. Grand et al. carried out a similar investigation on France and Germany's systems, highlighting the problems with a deep penetration of not-programmable sources and the need for backup of traditional generation capacity unless large storage systems are installed [7]. Heide et al. studied the all the European electrical systems, focusing on wind and solar sources, finding that the solar fraction should increase to achieve highest RES penetration [8].

As far as Italy is concerned, Romanelli proposed different proportions of electrical storage and base-load power plants, recognizing their criticality in high-RES penetrated scenarios [9]. Pierro et al. proposed a pathway to achieve 100% RES penetration in the Italian electricity system, transforming RES into dispatchable electricity thanks to the flexibility of hybrid PV plants: curtailment and batteries should coexist if the target is a cost optimization [10]. The increased penetration of not-programmable RES will also face problems of dispatchability, and, in some hours, the supplied electricity could be larger than the demand thus causing a surplus of energy. When overgeneration occurs, electricity must be recovered in short-term [11] or long-term storage [12], converted into different energy forms, or curtailed [13,14]. Other authors used LCA approach to evaluate the sustainability of electricity mixes of European countries in 2030, finding an average reduction of 42% in the impacts on climate change (with the only exception of Belgium [15]) and proving the impact of Italian PNIEC (forecast of 46% reduction of gCO2eq/kWh) [16].

Another possible modification of the future scenario is the concept of "Renewable Energy Community" introduced by the European Directive RED-II. This new entity could change the interactions among actors of the energy sectors and especially of the electrical one. Di Silvestre et al. investigated the interaction of Renewable Energy Communities with the Italian power system [17]. During the transition to decarbonization, the impact on residual generation profiles (from fossil fuel, in particular natural gas) is an open issue: peak power is only slightly reduced, while energy is definitely decreasing. This means that annual running hours (i.e., utilization factor) will decrease, with a strong impact on the economic performance and sustainability of traditional thermal-electric plants. This issue might also create serious problems for covering the plants' capital costs. Moreover, the so-called 'renewable energy policy paradox' could occur in the next decades: intermittent RES may reduce electricity selling prices and, hence, the profitability of new RES installations [18].

This study is based on a simplified approach, which can be used for every country once annual hourly energy balance data are known. It begins with the hourly demand and the power generation mix and considers increasing the non-programmable energy production from wind and photovoltaic several times. Of course, this may not be technically feasible, since it would mean that the power generation in a specific location can be increased by neglecting other issues, which is in general not possible. However, any other way of forecasting the potential energy power generation has inherently significant uncertainties at the country level. Similarly, the energy demand can change over the years, and this is an additional uncertainty. In any case, results in terms of RES penetration, surplus and residual generation obtained with this methodology are a useful basis for a preliminary system evaluation and in particular to assess the feasibility of surplus recovery and residual generation operability. Moreover, comparing results of this paper with a more detailed study carried out by the Italian TSO for 2030 and 2040 [19] shows that annual energy balances regarding RES penetration and RES surplus are very similar, confirming the validity of the proposed approach, at least for preliminary evaluations.

2. Energy Production and Surplus

As a case study, the Italian electricity production and consumption in 2019 was chosen, as this year was the last one which was still not affected by the strong change in energy consumption due to the pandemic. Data were derived from the reports of the Italian transmission system operator Terna [20], and an hourly time scale was considered in the study. In 2019 the Italian electricity mix had the composition reported in Figure 1. The contributions of fossil fuels and imports from abroad were not distinguished, as the focus of the study is mainly on renewables and their impact on the general energy management than in the actual energy mix.

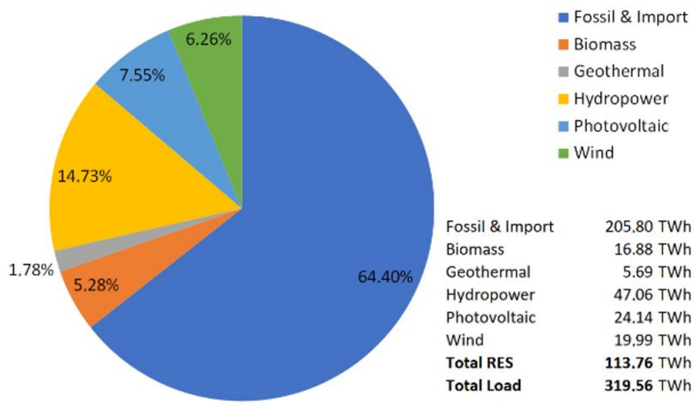

Figure 1. Energy mix for the electric energy supply in 2019.

In 2019, almost 65% of the energy supply came from fossil fuels and imports (F&I), around 15% from hydropower (H), 5% from biomass (B) and 2% from geothermal energy (G). As for the variable RES, the percentages are 7.5% and 6% for photovoltaic (PV) and wind (W), respectively.

As an example, in Figure 2, the energy mix for the supply of the electricity load on some typical days of 2019 is reported. The incidence of photovoltaic contribution during the central hours of the day and the different contribution of variable renewable energies according to the season are apparent. In Figure 3, the monthly energy production from traditional sources and from RES is reported. With the current energy mix, and by considering a one-hour time scale, no RES surplus is reported, even in the summer months when PV plants produce the most.

In a generic year k, the hourly averaged power generation P^k_{gen} can be expressed as the sum of multiple contributions, as in Equation (1):

$$P^k_{gen} = P^k_{F\&I} + P^k_{PV} + P^k_W + P^k_G + P^k_H + P^k_B = P^k_{F\&I} + P^k_{RES} \quad (1)$$

where $P^k_{F\&I}$ is the sum of the power generated by fossil fuels and that imported from abroad, P^k_{PV} is the power generated by photovoltaic plants, P^k_W that coming from wind power plants, P^k_G that from geothermic power plants, P^k_H that from hydro power plants and P^k_B that from biomass. The sum of the last five terms is the power from renewables P^k_{RES}.

If no storage has been considered, a balance between the load P^k_{load} and the power generated P^k_{gen} has to be met. In case of a large amount of non-regulated renewable energies, a power surplus P^k_{sur} may occur (Equation (2)):

$$\begin{cases} P^k_{sur} = P^k_{gen} - P^k_{load} & if \quad P^k_{gen} > P^k_{load} \; and \; P^k_{F\&I} = 0 \\ P^k_{sur} = 0 & if \quad P^k_{gen} = P^k_{load} \; and \; P^k_{F\&I} > 0 \end{cases} \quad (2)$$

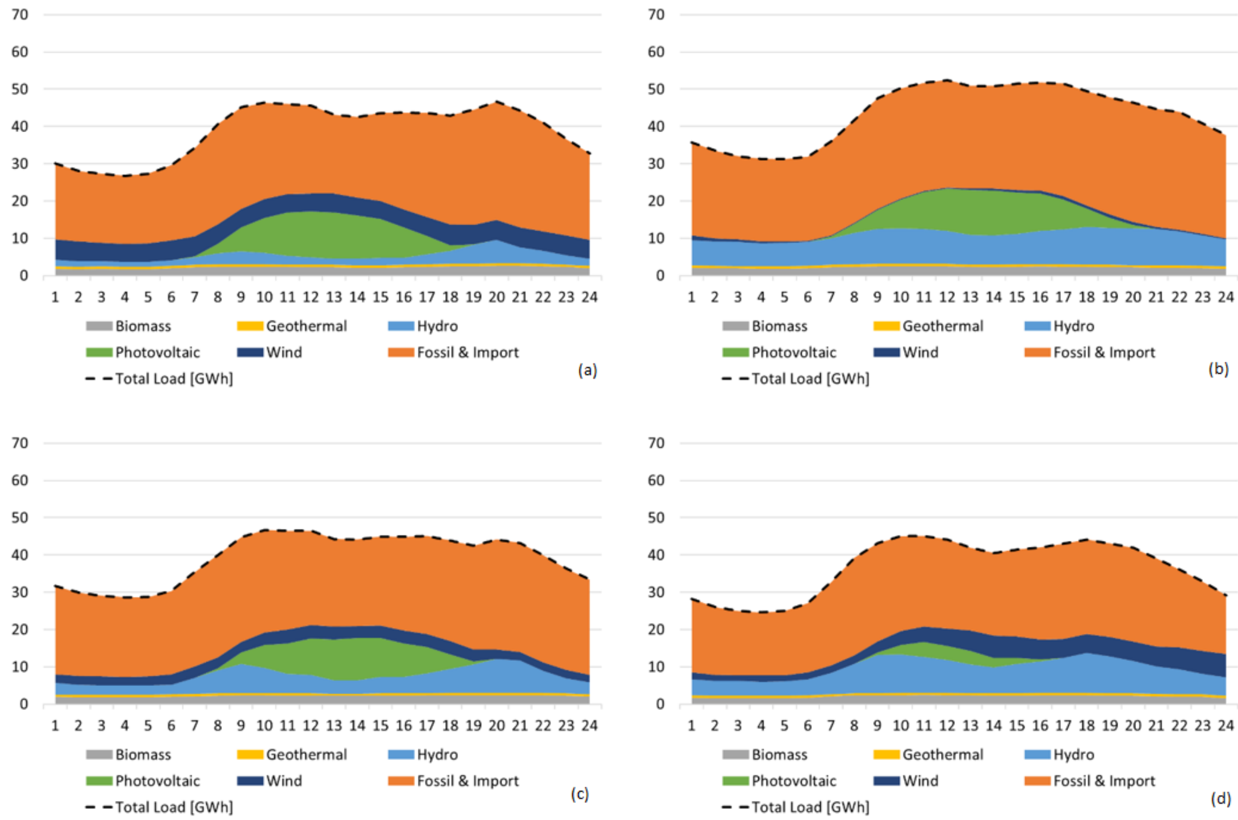

Figure 2. Energy mix for the electric energy supply on (**a**) 21 March, (**b**) 21 June, (**c**) 20 September and (**d**) 20 December 2019.

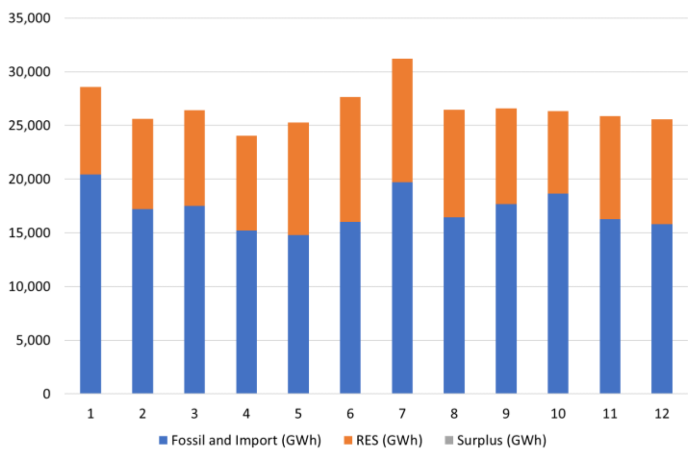

Figure 3. Monthly energy production from renewables, from fossil fuel and imports, and renewable energy surplus.

In 2019, indicated with $k = 0$, the hourly average power from renewables, P^0_{RES}, was never sufficient to satisfy the power load (P^0_{load}). Therefore, $P^0_{F\&I}$ is always greater than 0 and $P^0_{sur} = 0$.

To investigate the impact of an increase in renewables on the energy mix, a hypothetic condition was considered in which, with the same energy demand, the production from wind and photovoltaic is increased. This assumption is purely hypothetical and does not consider many other aspects that would play a role if an actual change in the energy mix would occur. In other terms, the feasibility of an increase in renewables was not investigated, but the impact that such an increase would bring to the generation system under some simplified assumptions. In particular, the following simplified assumptions were considered:

- Hour electricity load remains the same, independently from the energy mix composition.
- No economic analyses were performed relating to electricity cost or feasibility of an increased power transmission.
- Generation from hydropower, biomass and geothermal plants remains the same. This assumption is justified by considering that these renewable sources would require a massive investment to be increased, or that the best sites have been already exploited.
- Generation from fossil fuel could be modified at will, even entirely shut down in some hours. No considerations on the technical or economic feasibility of this operation have been made.
- Regarding the photovoltaic and wind plants:
    - No assumptions are made regarding the economic and geographical feasibility of such an increase in power from photovoltaic and wind plants.
    - It is supposed that the additional photovoltaic and wind plants produce energy with the same profile of the existing ones.
    - The generation profile is just numerically multiplied for a factor depending on the scenario.

With reference to a generic year k, the previous assumptions can be expressed in mathematical form as in Equation (3).

$$\begin{cases} P_G^k = P_G^0 = const \\ P_H^k = P_H^0 = const \\ P_B^k = P_B^0 = const \end{cases} \rightarrow \begin{cases} P_{PV}^k = mP_{PV}^0 \\ P_W^k = nP_W^0 \end{cases} \rightarrow P_{load}^k = P_{load}^0 = const \quad (3)$$

Two case studies were initially considered corresponding to a future scenario in line with the targets of 2030 and 2040, respectively:

- Case 1 with a production from photovoltaic and wind which is thrice and twice the current production, respectively (k = 1).
- Case 2 with a production from photovoltaic and wind which is four times and thrice the current production, respectively (k = 2).

From a mathematical point of view, the two scenarios can be described as in Equations (4) and (5), respectively. As a results, in Table 1, a summary of the values considered in the study is reported.

$$P_{sur}^1 = P_{gen}^1 - P_{load}^0 = \left(P_{F\&I}^1 + 3P_{PV}^0 + 2P_W^0 + P_G^0 + P_H^0 + P_B^0\right) - P_{load}^0 \qquad P_{sur}^1 \geq 0 \quad (4)$$

$$P_{sur}^2 = P_{gen}^2 - P_{load}^0 = \left(P_{F\&I}^2 + 4P_{PV}^0 + 3P_W^0 + P_G^0 + P_H^0 + P_B^0\right) - P_{load}^0 \qquad P_{sur}^2 \geq 0 \quad (5)$$

Under the assumptions of Case 1, the energy mix for the electric energy supply in some typical days would be that reported in Figure 4. The amount of energy from renewable sources is increased but far from covering the energy total demand; a great use of energy from fossil fuels would be still necessary. Only in some central hours of the day during mid seasons there is a match between the energy from renewable and the load, or even a small surplus. This is a favorable condition in which winds and solar irradiation are of good intensity even though not as strong as in winter and summer, respectively, and load is not as high as in summer. By considering the monthly production, the amount of energy from fossil fuels (and imports from abroad), energy from renewable and surplus from renewables will be that reported in Figure 5. Even with such an increase in the amount of renewable energy production, the surplus of renewable energy would be very limited and only available during some months of the year.

Table 1. Summary of the considered energy production.

		Base	Case 1	Case 2
		1 PV–1 W	**3 PV–2 W**	**4 PV–3 W**
Total load	[TWh]	319.56	319.56	319.56
Wind	[TWh]	19.99	39.99	59.98
Photovoltaic	[TWh]	24.14	72.42	96.55
Hydropower	[TWh]	47.06	47.06	47.06
Biomass	[TWh]	16.88	16.88	16.88
Geothermal	[TWh]	5.69	5.69	5.69
Energy from RES	[TWh]	113.76	182.03	226.16
Fossil and Import	[TWh]	205.80	141.88	113.05
RES surplus	[TWh]	0	4.35	19.65
RES penetration		35.6%	55.6%	64.6%

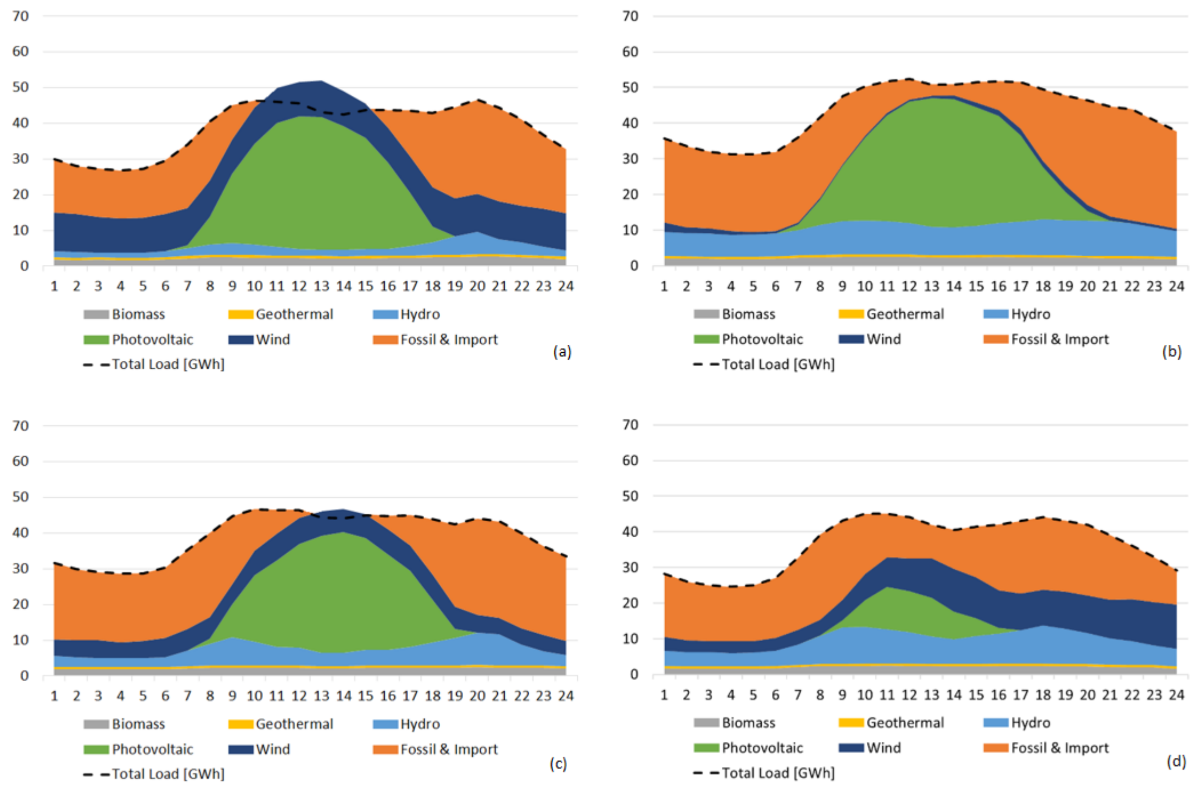

Figure 4. Case 1 with thrice the production from photovoltaic and twice the production from wind. Energy mix for the electric energy supply on (**a**) 21 March, (**b**) 21 June, (**c**) 20 September and (**d**) 20 December 2019.

If, still considering the previous assumptions, the production from photovoltaic and wind plants is increased by 4 and 3 times, respectively (Case 2), the energy production from renewables would be that reported in Table 1. In this case, the production from renewables would be massive but still the energy surplus would be limited to a portion of a day (central hours) and of reduced entity. As an example, in Figure 6, the energy mix for the electric energy supply on some typical days of 2019, under the assumptions of Case 2, is reported.

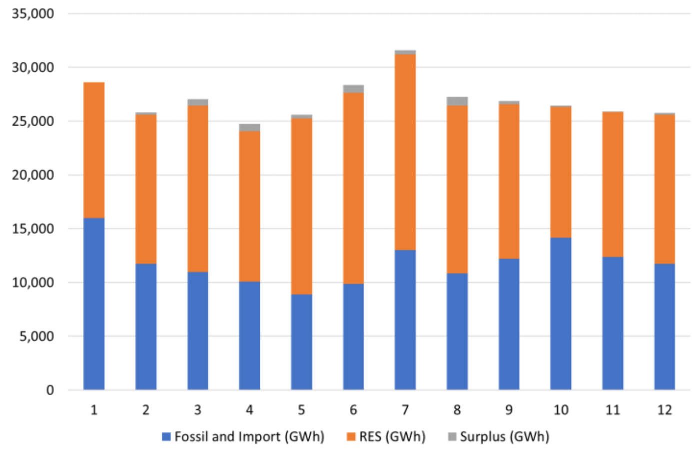

Figure 5. Case 1 monthly energy production from renewables, from fossil fuel and imports, and renewable energy surplus with thrice the production from photovoltaic and twice the production from wind.

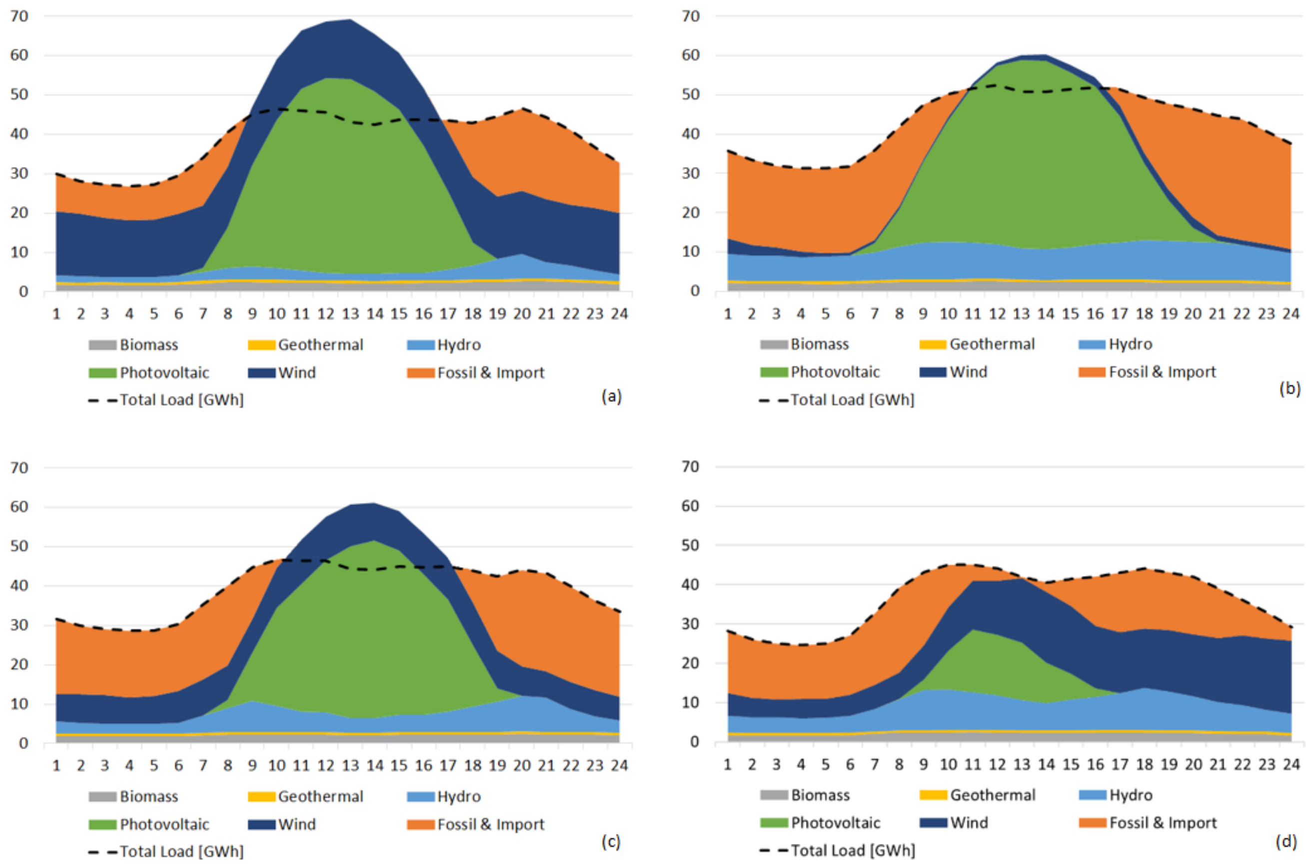

Figure 6. Case 2 with four times the production from photovoltaic and thrice the production from wind. Energy mix for the electric energy supply on (**a**) 21 March, (**b**) 121 June, (**c**) 20 September and (**d**) 20 December 2019.

The increase in power production from renewables is apparent, especially in the central hours of the day. However, a big portion of the load has still to be satisfied by traditional sources, especially far from the central hours of the day. In this case, the monthly energy production from renewable is greater, but still the contribution from fossil fuels and imports from abroad is significant. The renewable energy surplus is increased, but it is still marginal in comparison the whole energy demand (Figure 7). It has to be considered that this condition would be very difficult to reach for obvious reasons of ground/roof occupancy (in the case of photovoltaic plants) and sites with high wind availability. As the most productive and easy to access sites are those that were first exploited, it may be supposed, in fact, that without the introduction of a new groundbreaking technology, the sites that will be exploited for the new installations would be less and less appealing from the energy production point of view. However, repowering of existing onshore wind power installation is an opportunity to increase the capacity and also an offshore solution is feasible in many Italian locations.

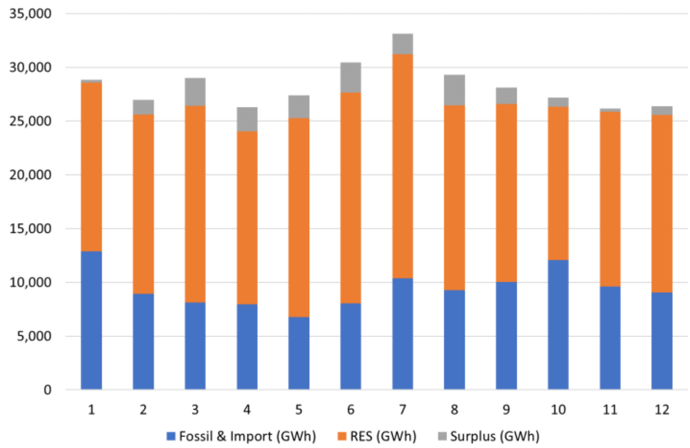

Figure 7. Case 2 with monthly energy production from renewables, from fossil fuel and imports, and renewable energy surplus with four times the production from photovoltaic and thrice the production from wind.

3. Size and Operating Hours of Non-RES Generators

As shown in Figures 2, 4 and 6, due to the uneven production from renewable energy sources, there are periods during the day (especially in the central hours) where the generation from renewables is strongly concentrated. On the other hand, there are hours, especially in the morning and in the evening, when the energy request is still high, but the insolation is low. In these hours, there is still a strong contribution from fossil-fuel-based generators and/or energy imports from abroad. In Figure 8, the distribution of the hourly averaged power requested to compensate renewables and to satisfy the energy demand is reported. The figure refers to the actual data related to 2019. A bin size of 5 GW is considered for the sake of simplicity. By analyzing the figure, it may be noticed that:

- The maximum power requested is around 40 GW, but it occurs only a few hours during the year.
- The most requested power is in the range 20–25 GW, but a power between 15 and 30 GW is requested for almost 75% of the year.

To further investigate the operating condition of the existing traditional plants, in Figure 9, the maximum, minimum and averaged value of the power from fossil fuel and imports for each hour of the day during the reference year is reported. It is interesting to notice that there are no hours when the power request is null, or, in other terms, there are no hours when the hourly averaged power from renewables is sufficient to satisfy the Italian energy request.

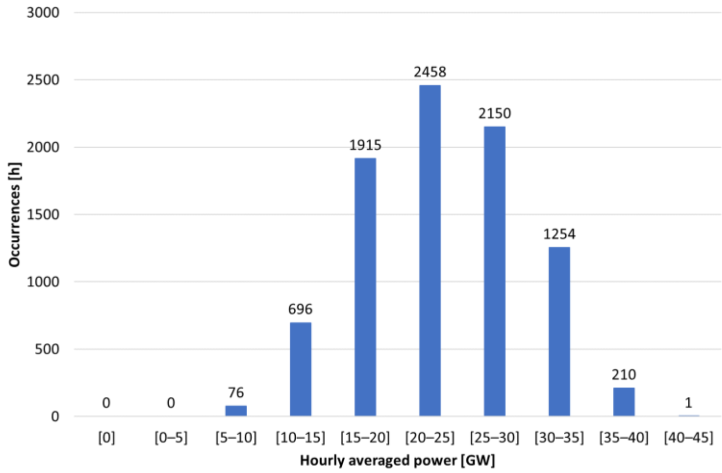

Figure 8. Distribution of hourly averaged power of non-renewable sources during the reference year (2019).

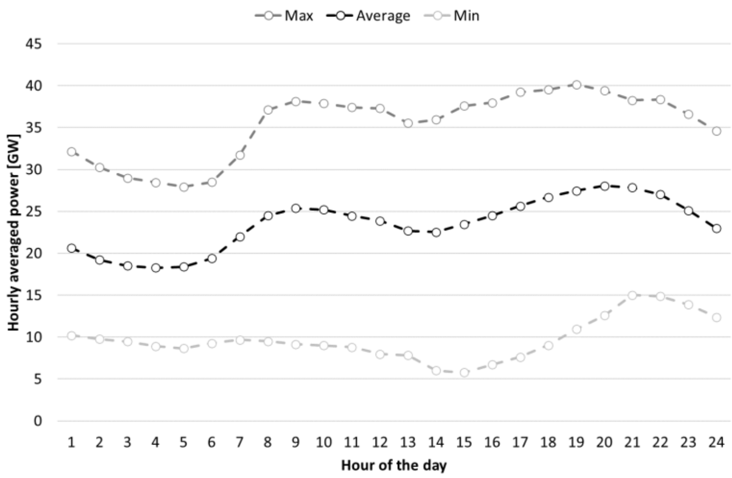

Figure 9. Hourly averaged power of non-renewable sources during the day in the reference year (2019); average, maximum and minimum values.

In Figures 10 and 11, the same analysis is performed for the Case 1 scenario. The most populated range of powers is between 10 and 25 GW, with a total occurrence nearly 60% of the year. A maximum power in the range 35–40 GW is still requested in some hours of the day to compensate for the lack of production from renewables, but with a lower number of occurrences. If one considers the range 0–5 GW, corresponding to a null or low usage of non-RES sources, the occurrences will increase to more than 15% of the year. From Figure 11, it is apparent that these periods of no usage of non-RES sources are specifically located in the middle hours of the day (minimum power equal to zero), whereas during the morning, evening and night, non-RES sources still need to be used. In other terms, the maximum installed capacity, which is necessary to sustain the energy supply when a lack of production from RES occurs, would be more or less the same as that with the current RES penetration (40/45 GW in base case versus 35/40 GW in Case 1), but with a lower usage over the year.

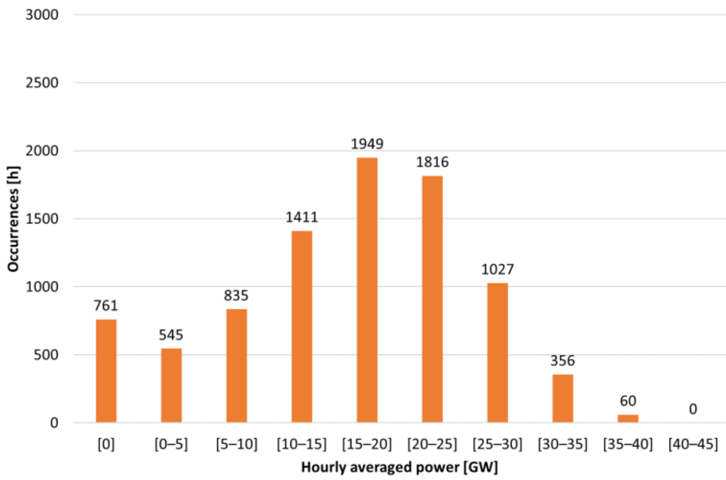

Figure 10. Distribution of hourly averaged power of non-renewable sources during the reference year in Case 1.

Figure 11. Hourly averaged power of non-renewable sources during the day in Case 1; average, maximum and minimum values.

This result is even more apparent if the case with four times the photovoltaic production and thrice the wind production is considered (Case 2, Figures 12 and 13). In this case, the most populated bins are again those in the range 10–25 GW, but with a total occurrence of 50% of the hours in the year. Still, the maximum capacity is in the range of 35–40 GW, but only for 0.2% of the time. As far as it concerns the range of 0–5 GW, the occurrence is 28%. In this regard, it may be noticed that the non-usage of non-RES sources may occur almost in each hour of the day during the year. Therefore, it is stressed how an increase in the penetration of renewables might pose some problems in the way the lack of production is compensated. The big difference between installed capacity and operating hours might be critical from the economic feasibility point of view of these plants, as the capital costs are related to capacity and the revenues to operating hours. Future electrical storage could be used to smooth these few spikes during the year, maybe reducing the required traditional generation capacity, but the utilization factor of the remaining plants is going to be strongly reduced.

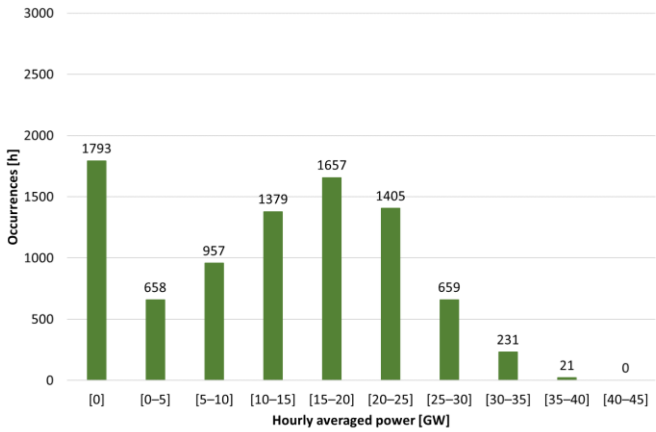

Figure 12. Distribution of hourly averaged power of non-renewable sources over the year in Case 2.

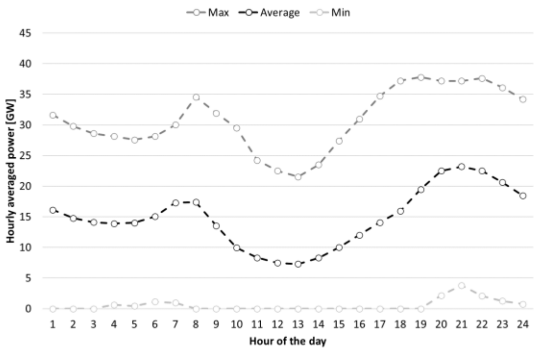

Figure 13. Hourly averaged power of non-renewable sources during the day in Case 2; average, maximum and minimum values.

4. Size and Operating Hours of RES Surplus Users

To further investigate the scenario of an increasing penetration of renewables, it is of interest to consider the operating conditions of the potential users of the RES surplus, otherwise curtailed. In Figure 14, the hourly averaged power of a hypothetical user of RES surplus and the corresponding operating hours are reported for Case 1. In Figure 15 the hourly surplus and number of occurrences during the year are shown for the same scenario. It is apparent that, even in the Case with a lower penetration of renewables, if no surplus curtailment is accepted, the installed power necessary to fully exploit the RES production would be significant (around 20–25 GW). However, the operating hours in these conditions would be limited. The users would be not in operation for the most part of the year (almost 8000 h on 8760). Moreover, the surplus energy is always concentrated in central hours of the day.

By increasing the renewables penetration as in Case 2, Figure 16, the situation would be not much different, with high maximum power requests but a limited number of operation hours. Due to this small annual utilization factor, the exploitation of this energy in a plant by changing energy vector or producing other byproducts (e.g., power to X systems) is very difficult.

Looking to hourly distribution of surplus (Figure 17), electrical storage seems the most obvious option. An intra-day storage could recover a portion of this energy, simply transferring the surplus from the central hours of the day to the evening/night, thus replacing some traditional fossil fuel generation. However, a detailed economic evaluation has to be carried out because, in some cases, the simple curtailment may be preferred to any other solution.

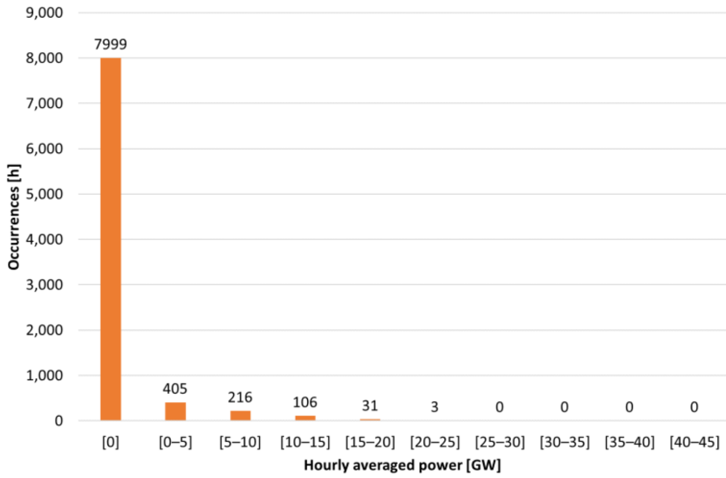

Figure 14. Distribution of hourly averaged power over the year of surplus users in Case 1.

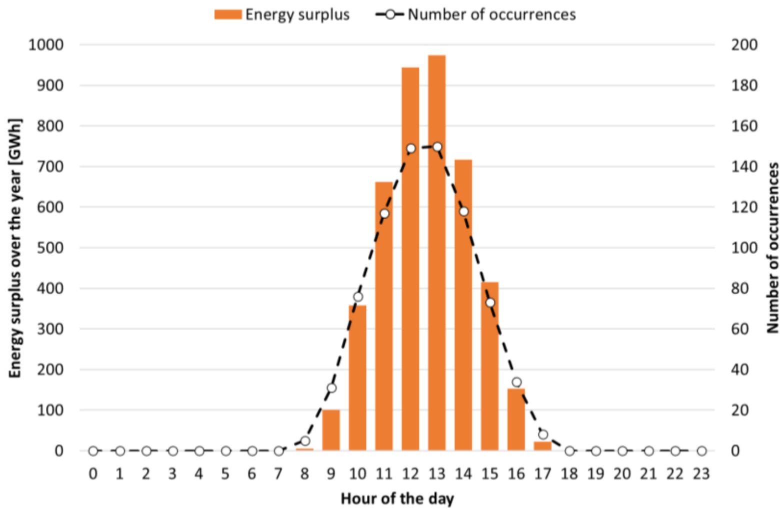

Figure 15. Distribution of hourly energy surplus over the year and number of occurrences in Case 1.

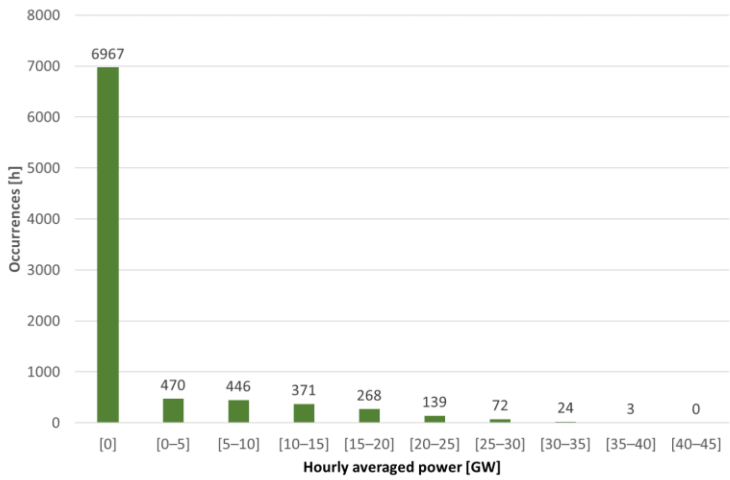

Figure 16. Distribution of hourly averaged power over the year of surplus users in Case 2.

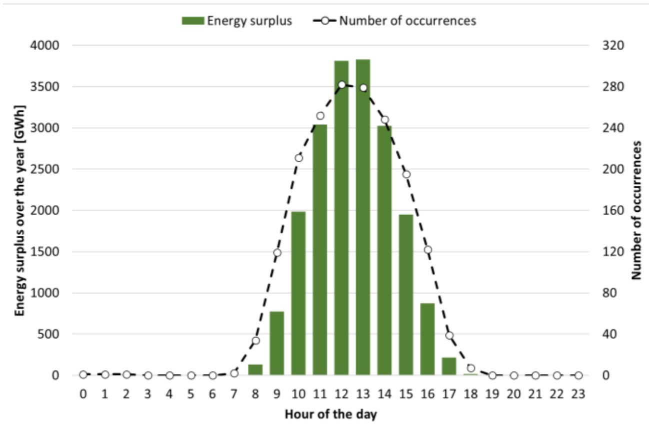

Figure 17. Distribution of hourly energy surplus over the year and number of occurrences in Case 2.

5. Extended Analysis

The previous analysis may be extended to different combinations of wind and photovoltaic penetration. In particular, a wind and a photovoltaic energy generation up to four times the current one was considered ($m = 1 \div 4; n = 1 \div 4$). The results are reported in Figure 18 in terms of:

- RES: amount of energy from renewables used to cover electricity demand over the year.
- F&I: amount of energy from fossil fuels and import used over the year.
- Surplus of energy from renewables over the year.
- RES%: percentage of annual electricity load satisfied with renewables.

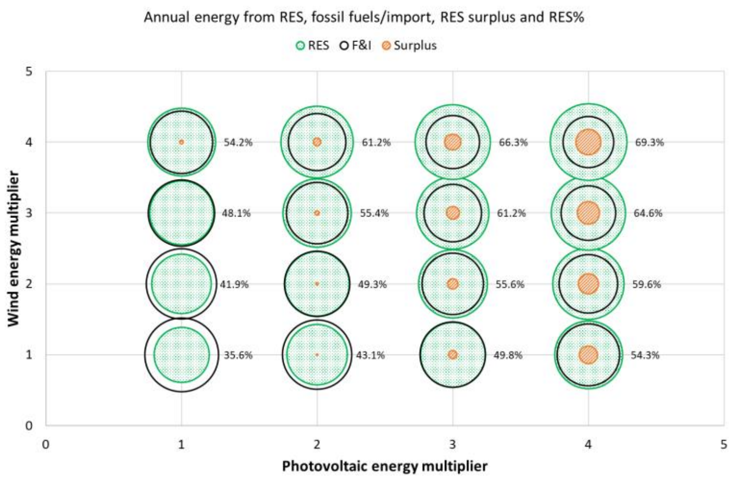

Figure 18. Annual energy from RES, fossil fuel/imports, RES surplus and RES% for different values of wind and photovoltaic productions.

In this figure, the amount of energy from renewables, from fossil fuels and imports, and the surplus from renewables are reported for each combination of wind and photovoltaic production $(m,\ n)$ as an area of different size. The share of renewables is reported for each scenario as a percentage value. This is calculated as (Equation (6)):

$$SH_{RES}^{m,n} = \frac{annual\ energy\ consumption\ form\ RES}{total\ annual\ energy\ consumption} \tag{6}$$

This representation allows a direct analysis of the impact that an increase in production from renewables would have on the energy systems. In more detail, the sizes of black and green circles allow the comparison between the energy consumption from renewables and from fossil fuel and imports. When the green circle is greater than the black circle, a renewable energy penetration greater that 50% is expected. The orange circle shows the surplus from renewables with the same scale.

A few considerations may be drawn:

- Even with four times the production of wind and PV, without electrical storage, the amount of energy from RES used over one year would be still far from 100%, and around 70%.
- To have a relevant energy surplus from renewables a significant increase in wind and PV production is necessary, and the latter seems to be more effective to generate a surplus thanks to its daily profile.
- By increasing the energy from RES, the amount of energy from fossil fuels and import decreases but not significantly. If wind and PV are multiplied by 4, residual generation is only halved.

With the same graphical representation, in Figure 19, the maximum and average operating power of the potential RES surplus users is reported for the same range of production from wind and PV. The difference between the areas of the blue and grey circle is proportional to the difference between the maximum and average operating power. For configuration with $m = 1$ and $n = 1$ or 2 there is no surplus from RES. With the capacity of photovoltaic generation of 2019, to have some surplus from RES, the wind capacity should be at least three times that of 2019. By increasing PV production, also the RES surplus increases. In the figure, the utilization factor of the potential RES surplus user is also reported as a percentage value. The utilization factor has been calculated as the ratio of the energy surplus to the maximum operating power multiplied by 8760 h per year (Equation (7)).

$$UF_{RES}^{m,n} = \frac{annual\ energy\ surplus\ from\ RES}{maximum\ power\ of\ RES\ surplus \times 8760} \quad (7)$$

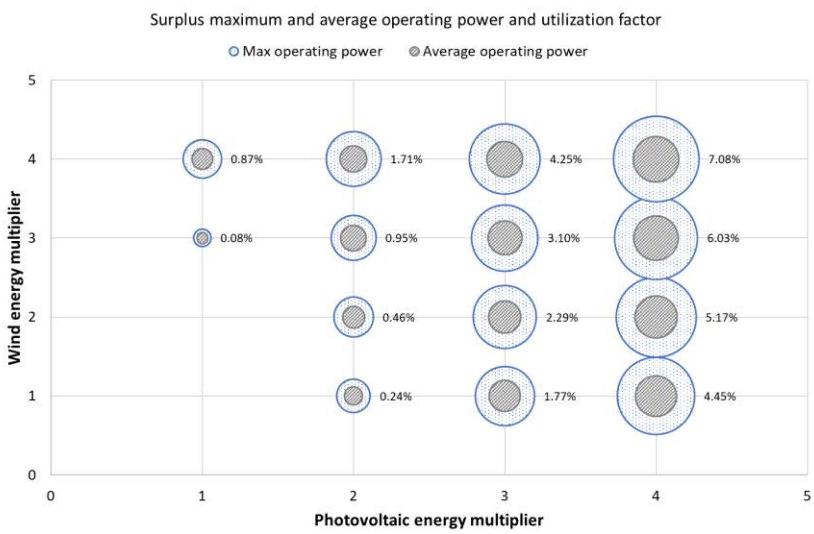

Figure 19. Maximum and average operating power for energy surplus user, and utilization factors for different values of wind and photovoltaic productions.

This parameter gives a conceptual indication of how proficiently the devices exploiting the energy surplus from RES are used. It is interesting to notice that this percentage is generally small and does not increase significantly when the energy production from RES increases: the utilization factors remain on values which are very low, far from those that would lead to a reasonable payback period for standard equipment.

The same analysis applied to fossil fuel power generation led to Figure 20, where the maximum and average operating power of the fossil energy sources (or imports) are reported for the same range of wind and PV. In addition, the utilization factor is shown as a percentage value. This was calculated as the ratio of the energy production from F&I to the maximum operating power multiplied by 8760 h per year (Equation (8)).

$$UF_{F\&I}^{m,n} = \frac{annual\ energy\ production}{maximum\ operating\ power \times 8760} \tag{8}$$

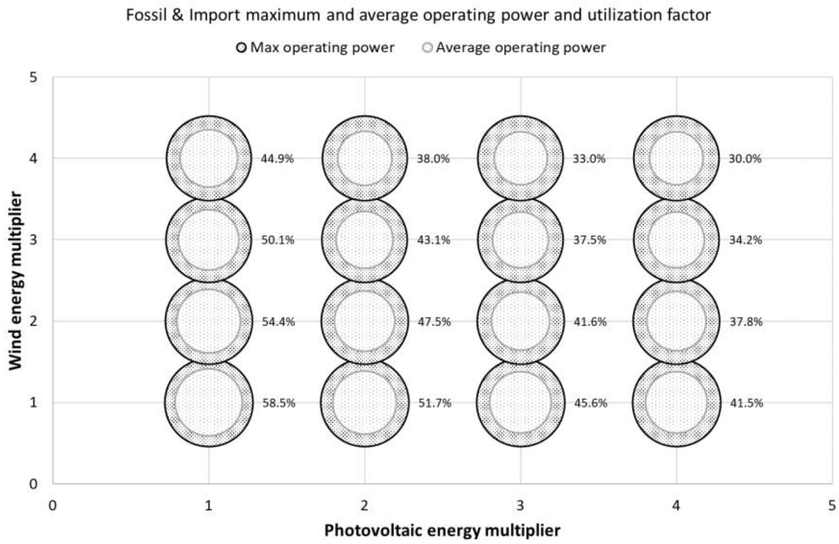

Figure 20. Maximum and average operating power for traditional energy sources, and utilization factors for different values of wind and photovoltaic productions.

As expected, the power requested to fully satisfy the energy demand over the year does not change significantly when energy production from RES increases. However, the utilization factor and the average power almost halve from the current condition to that with the maximum RES penetration, leading to potential criticalities of a feasible and efficient plant management.

All the numerical results shown in this study are reported in Table 2 for the sake of completeness.

Table 2. Summary of the numerical results found in this study.

						F&I			RES Surplus		
PV	**W**	**Surplus [TWh]**	**F&I [TWh]**	**RES [TWh]**	**RES%**	**Max P. [GW]**	**Av. P. [GW]**	**Utiliz. Factor**	**Max P. [GW]**	**Av. P. [GW]**	**Utiliz. Factor**
1	1	0	205.799	113.764	35.6%	40.15	23.49	58.5%	0	0.00	0.00%
2	1	131	181.791	137.771	43.1%	40.15	20.92	51.7%	6.1	1.90	0.24%
3	1	2976	160.498	159.064	49.8%	40.15	19.54	45.6%	19.2	5.44	1.77%
4	1	12,551	145.936	173.627	54.3%	40.15	19.76	41.5%	32.2	9.14	4.45%
1	2	0	185.806	133.757	41.9%	38.97	21.21	54.4%	0.0	0.00	0.00%
2	2	348	162.016	157.546	49.3%	38.97	18.77	47.5%	8.6	2.70	0.46%
3	2	4351	141.880	177.682	55.6%	38.97	17.74	41.6%	21.7	5.72	2.29%
4	2	15,725	129.116	190.446	59.6%	38.97	18.00	37.8%	34.7	9.91	5.17%
1	3	12	165.825	153.737	48.1%	37.79	18.96	50.1%	1.7	0.74	0.08%
2	3	922	142.597	176.965	55.4%	37.79	16.76	43.1%	11.1	3.69	0.95%
3	3	6567	124.104	195.459	61.2%	37.79	16.05	37.5%	24.2	6.39	3.10%
4	3	19,651	113.049	206.513	64.6%	37.79	16.23	34.2%	37.2	10.96	6.03%
1	4	613	146.433	173.129	54.2%	37.26	17.22	44.9%	8.0	2.39	0.87%
2	4	2444	124.127	195.436	61.2%	37.26	15.25	38.0%	16.3	3.94	1.71%
3	4	10,065	107.609	211.954	66.3%	37.26	14.70	33.0%	27.1	6.99	4.25%
4	4	24,618	98.024	221.539	69.3%	37.26	14.86	30.0%	39.7	11.38	7.08%

6. Conclusions

This study investigated the scenario of an increasing penetration of renewables in Italian electricity generation mix towards 100% RES. Starting from the real 2019 load and generation hourly profiles, PV and wind generation were multiplied by an increasing factor, while the electricity demand is assumed to remain the same. The adopted methodology completely neglects issues regarding the feasibility of such modification or the impact on the electrical system, focusing on the hourly energy balance of national load. This approach is a sort of 'best case' from renewable energy point of view, and the results must be considered as upper limits for renewable penetration. The comparison with more detailed studies reveals almost the same results, despite the simplicity of this methodology. Results showed that even with a factor of four (PV and wind energy generation four times those in 2019), RES penetration is far from 100%, reaching only 70%, while traditional (fossil) residual generation is only halved. Moreover, residual capacity (from traditional fossil sources or imports), which is necessary to support the system when renewable generation is not sufficient, is still very high (35–40 GW). With the increase in non-programmable renewables, the traditional plants reduce their operating hours and show frequent modulation and start–stop. This change in the operation profile will obviously affect the economics of traditional power plants.

The analysis focused also on RES surplus and its potential users, such as electrical storage and "power-to" systems. Electricity surplus from renewables will occur only a few hours in a year and mostly in central hours of the day. Due to the small annual utilization factor, the exploitation of this energy is very difficult, especially in plants producing other byproducts (e.g., power-to-X systems). The adoption of electricity storage to shift surplus from days to nights seems more suitable from an energy point of view, and it is the subject of ongoing studies. Impacts on national electrical system with energy flows and import/export with neighboring countries will also be the object of future research.

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