Assessing the regional redistributive effect of renewable power production through a spot market algorithm simulator: the case of Italy

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IAEE Online
June 8, 2021

Background and motivation

- A large number of publicly financed measures have been implemented worldwide with the aim of advancing renewable generation deployment thus reducing the emission of pollutants, typical of conventional power generation
- An impressive expansion in installed capacity has been attained: in 2019 combined solar and wind capacities have exceeded the 1200 GW threshold, representing around the 17% of global installed capacity
- The early economic literature on the impact of increasing renewable production on wholesale electricity markets has mainly focused on the "merit-order effect"
- However, more recent literature has highlighted that:
  - RES generation may not uniformly decrease the wholesale price
  - RES, notably solar and wind, displace fossil fuel units with different level of efficiency: the production cycle largely determines the substitution effect
  - In power markets organised as two or more inter-connected sub-markets with locational pricing mechanisms, the localisation of renewable has a relevant impact on prices because of network congestions

Paper's objective

- We provide an original and novel approach in the assessment of RES impact on wholesale markets
- We developed a tool called M.I.D.A.S. (Italian Day-Ahead Market Solver) which simulates the hourly equilibrium (price-quantity) of the Italian day-ahead market taking into account all transmission constraints between the 11 national zones and the import from neighbouring countries
- The algorithm is trained over 80 million hourly observations
- M.I.D.A.S. is employed to study the sensitivity of market equilibria to changes in production from sun and wind power plants, at different locations and for different production increases
- We study the consequences on hourly zonal prices, zonal generation mix, network congestion and zonal balance between demand and supply (as opposed to existing literature focusing only on average price figures)

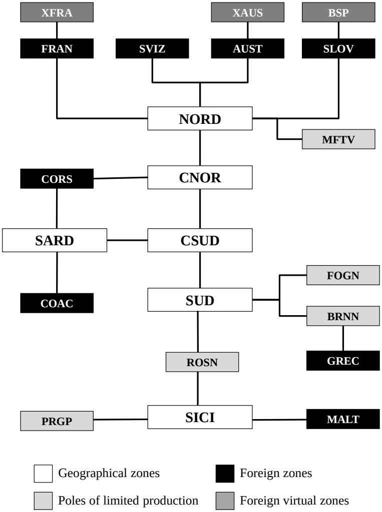
Italy is an ideal case study

- Renewables sources play an important role in Italian generation mix: in 2018, they represent the 40% of Italian power production
- Italy has challenging targets for solar and wind production according to the National Integrated Energy and Climate Plan:
  - Solar: 73.1 Twh in 2030 as compared to 22.7 Twh in 2018 (a 222% increase)
  - Wind: 41.5 TWh in 2030 as compared to 17.7 Twh in 2018 (a 134% increase)
- It has an interconnected power market with zonal pricing
- It has heterogeneous inter-zonal transmission capacities and zonal production capabilities depending on historical and geographical reasons
- Electricity prices have been higher than those in neighbouring countries because Italy has a generation mix strongly dependent on gas
- Market data are publicly available

The Day-ahead market

- We focus on the Italian day-ahead market (MGP, Mercato del Giorno Prima) which is organised in 24 hourly sessions and it operates in the form of uniform price auction
- Market participants submit a quantity-price pair for each hour: all the requests are ranked according to the merit order rule, from the cheapest to the most expensive in the case of offers and vice-versa for bids
- The hourly market price is determined by the intersection of the demand and the supply curves following an iterative procedure
  - If the equilibrium respects the transmission constraints between regions a single price emerges
  - If, on the contrary, a constraint is saturated the geographical market is split in two: an upstream and a downstream markets
  - The auction is repeated on the two sub-markets, taking into account the flows between regions to the upper bound of transmission capacity, and two zonal prices result
  - The splitting procedure is iterated until all inter-zonal constraints are fulfilled

The zonal layout



- There are 22 zones, grouped into 4 types:
  - 6 Italian geographical zones
  - 5 Poles of limited production
  - 8 Foreign interconnected zones
  - 3 Foreign virtual zones (market coupling)
- A "ring" exists in the central zones since 2015 (before three topology)
- The two, one and three zonal configurations are the most likely
- In case of congestion:
  - producers receive the zonal prices
  - buyers pay the National Single Price (PUN)

Results' overview (1/2)

- When power markets are organised on zonal-basis with locational price signals and final buyers pay a unique price for the power bought in the day-ahead market, **a larger renewable production decreases the average zonal prices, but the distribution of benefits depends on power plants' localisation**

- PUN is an average of zonal prices weighted for the zonal purchases; it gives higher weight to zones with larger demand (not necessarily those in which the zonal price reduction is the more important)

  ⇒ **Concentrating the additional production in zones with larger demand is more efficient in reducing the unique wholesale price**

- For 1% and 20% increases in supply, Solar and SmRES achieve the largest reduction in PUN; for 5% Solar/SmRES and Wind attain the same reduction; for 10% increment, Wind seems to be more efficient

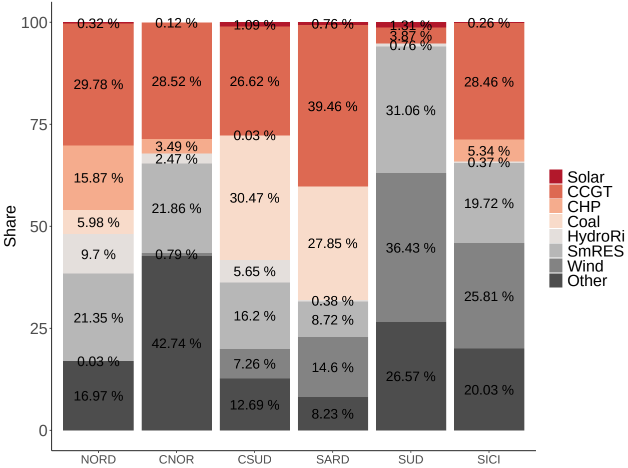
Results' overview (2/2)

- Given than Solar/SmRES, Wind and Hydro units do not bid at zero price in our data, the extent to which they can compete between them and with thermal generation is not straightforward
- **There is competition between renewables sources (Solar/SmRES, Wind, Hydro) but there is also competition between renewables and thermal sources**
- We quantify the substitution effect across renewables and between renewables and thermal for all regions and for all considered increase in supply

Data

- We match two databases
  - GME database, covering the 2015-2018 period, with hourly information on:
    - Submitted price/quantity pair for each bid/offer from a unit
    - Import/export quantity resulting from the implicit market coupling auction
    - Transmission limits across zones (in Mwh)
  - REF-E database which identifies the production technology of power plants
    - We restrict our analysis to 7 technologies: Solar, SmRES, Wind, HydroRi, CCGT, Coal and CHP
- We are able to cover the 96.5% of the total quantity submitted in 2018

Zonal generation mix



M.I.D.A.S algorithm

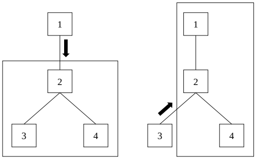
- GME algorithm:
  - In general, the uniform purchase price auction is solved by finding the the equilibrium that maximizes system welfare under constraints
  - However, in practice the Uniform Purchase Price Optimization (UPPO) search procedure used by the GME rather relies on heuristics
  - The main idea behind this method is to fix the uniform purchase price at some level and repeatedly apply the UPPO procedure to find a solution which could be eventually modified in order to satisfy the constraints
- M.I.D.A.S. (Italian Day-Ahead Market Solver) algorithm:
  - It reproduces the iterative market splitting logic to find the equilibrium
  - It is written in C++ and it is trained using 2015-2018 real hourly bid/offer data
  - We consider 10 iterations a good compromise between time and precision (the algorithm solves all the hourly equilibria for the whole year in less than 1 minute)
  - When multiple solutions are found, we select the one that is associated to the largest social welfare defined as:

$$W = \sum_{b \in B} p_b q_b - \sum_{o \in O} p_o q_o$$

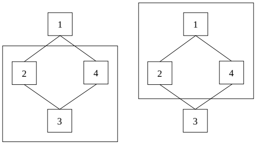
Assumptions

- We needed to introduce two random elements in the algorithm due to the different logic behind the algorithms and incomplete information:

The starting node



The loop splitting rule



- Making a choice implies the saturation of different links and hence different congestion patterns/zonal grouping

Performance

- As a measure of performance, we show the statistics on the amplitude of the differences (in absolute value) between hourly zonal real and simulated prices in 2018 (left table) and the average annual zonal prices and PUN (right table)
- The 2018 mean error is 0.44 euro

Diff in €	%
< 0.01	85.210
< 0.1	88.394
< 1	95.390
< 5	98.318
< 10	99.105
< 15	99.401
< 50	99.851
< 100	99.981

Price	Simul	True
NORD	60.76	60.71
CNOR	61.34	61.07
CSUD	60.89	60.94
SARD	60.48	60.69
SUD	59.27	59.37
SICI	69.40	69.49
PUN	61.34	61.31

- Simulated accepted quantity tends to be inferior to the real one in most cases with percentage differences that, overall, are between 0.2 and 1%
- Concerning congestion, M.I.D.A.S tends to slightly under-estimate the occurrence of the 2 zonal configuration in favour of the 4, 5 and 6 ones

Simulations

- We simulate 7 scenarios

Scenarios	Definition
UG	Uniform increase in CCGT
UW	Uniform increase in Wind
US	Uniform increase in Solar and SmRES
DW	Increase in Wind in SARD, SUD, SICI
DDW	Increase in Wind in NORD, CNOR, CSUD
DS	Increase in Solar and SmRES in SARD, SUD, SICI
DDS	Increase in Solar and SmRES in NORD, CNOR, CSUD

- For each scenario, we consider 1% (2.5 Twh), 5% (12.5 Twh), 10% (25 Twh) and 20% (50 Twh) increase in total production
- We analyse the impact on average prices (zonal and PUN), accepted quantities, congestion and export/import balance

Uniform increase

Zone	Baseline	1%	5%	10%	20%
NORD	60.76	59.99	57.43	54.45	**49.23**
CNOR	61.34	60.62	57.80	53.31	44.30
CSUD	60.89	59.93	56.62	52.16	43.36
SARD	60.48	59.14	52.17	43.94	**32.86**
SUD	59.27	58.41	54.99	50.46	41.71
SICI	69.40	68.15	63.42	57.69	47.13
PUN	61.34	60.50	57.46	53.64	**46.69**

Table: UW Scenario (€/Mwh)

Zone	Baseline	1%	5%	10%	20%
NORD	60.76	60.03	57.42	54.42	49.46
CNOR	61.34	60.91	57.63	53.16	**42.54**
CSUD	60.89	59.90	56.60	52.01	**42.21**
SARD	60.48	59.47	53.70	45.30	33.94
SUD	59.27	58.40	54.93	49.90	**40.05**
SICI	69.40	67.84	62.21	55.29	**43.36**
PUN	61.34	60.54	57.41	53.47	**46.18**

Table: US Scenario (€/Mwh)

- The strength of the zonal merit order effect is heterogenous across zones; the effect is stronger for Solar/SmRES or Wind according to the percentage increase
- The impact on average PUN is very similar for the 2 technologies
- Counterfactual check: increasing 20% CCGT production results in an average PUN which is about 4 €/Mwh higher

Heterogenous increase in Wind

Zone	Baseline	1%	5%	10%	20%
NORD	60.76	60.25	58.63	57.25	55.37
CNOR	61.34	61.36	59.68	58.37	56.60
CSUD	60.89	59.99	57.39	54.99	52.25
SARD	60.48	58.21	46.65	37.78	**26.81**
SUD	59.27	58.23	53.91	48.50	**39.76**
SICI	69.40	67.46	60.43	52.35	**40.37**
PUN	61.34	60.65	58.03	55.53	52.11

Table: DW Scenario (€/Mwh)

Zone	Baseline	1%	5%	10%	20%
NORD	60.76	59.83	56.63	52.66	**45.32**
CNOR	61.34	60.73	56.41	50.94	**40.84**
CSUD	60.89	59.92	56.44	51.39	**42.66**
SARD	60.48	59.54	55.97	51.12	42.50
SUD	59.27	58.58	55.72	51.14	42.56
SICI	69.40	68.96	66.87	63.41	58.05
PUN	61.34	60.49	57.21	52.88	**45.06**

Table: DDW Scenario (€/Mwh)

- Zonal average prices decrease more where the additional production is located (in the Southern zones the decline is more important)
- For PUN, production is better localised in the Norther zones (largest demand)
- In the DDW scenario, PUN shrinks more than in Uniform simulations and zonal prices tend to converge with the exception of SICI

Heterogenous increase in Solar/SmRES

Zone	Baseline	1%	5%	10%	20%
NORD	60.76	60.23	58.68	57.30	55.54
CNOR	61.34	61.16	59.48	58.98	59.42
CSUD	60.89	60.04	57.18	54.99	53.57
SARD	60.48	58.79	48.01	37.42	**27.84**
SUD	59.27	58.16	53.04	45.62	**36.63**
SICI	69.40	66.74	57.74	47.64	**36.19**
PUN	61.34	60.59	57.85	55.19	52.33

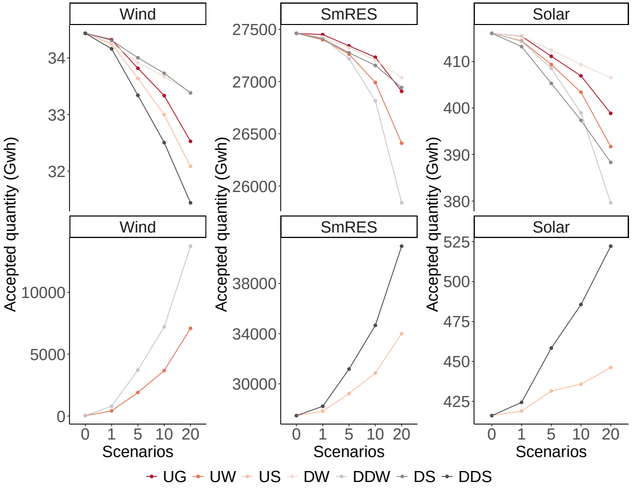
Table: DS Scenario (€/Mwh)

Zone	Baseline	1%	5%	10%	20%
NORD	60.76	59.82	56.55	52.79	**45.56**
CNOR	61.34	60.30	56.20	51.43	**39.98**
CSUD	60.89	59.95	56.67	52.20	**41.80**
SARD	60.48	59.49	56.09	51.86	41.49
SUD	59.27	58.60	55.91	51.89	41.70
SICI	69.40	68.94	67.13	64.37	58.18
PUN	61.34	60.44	57.21	53.27	**44.88**

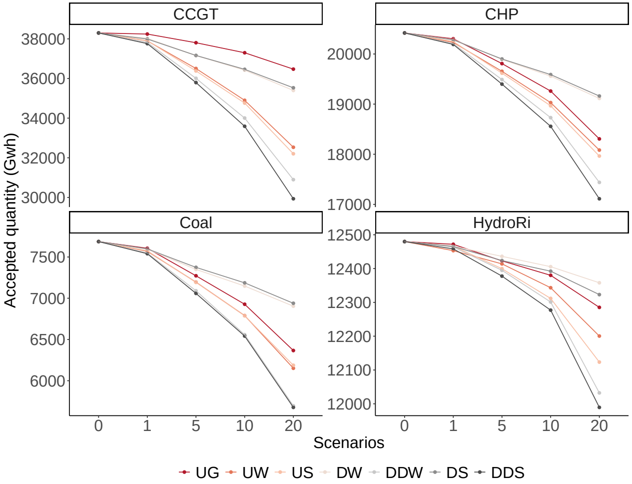
Table: DDS Scenario (€/Mwh)

- The impact on zonal average prices is the same as in the previous case
- The strongest decrease in PUN across all simulations is found in the DDS scenario for a 20% increase in production
- The impact on PUN is exactly the same of Wind for a 5% increase, while for a 10% increase, Wind outperform Solar and SmRES

Impact on quantities (Solar/SmRES and Wind): NORD



Impact on quantities (Other technologies): NORD



Congestion

- We analyse in details the impact on congestion for each considered scenarios

Z	Base	1%	5%	10%	20%
1	38.40	38.90	39.27	36.58	**35.33**
2	43.02	42.18	39.43	36.64	35.08
3	14.87	14.83	14.76	15.87	**18.12**
4	3.45	3.67	5.20	8.21	8.71
5	0.25	0.38	1.17	2.45	2.41
6	0.01	0.03	0.18	0.25	0.34

Table: US scenario

Z	Base	1%	5%	10%	20%
1	38.40	39.00	38.61	36.88	31.96
2	43.02	42.93	44.20	45.56	**47.67**
3	14.87	14.13	13.45	14.59	19.27
4	3.45	3.63	3.30	2.61	**1.05**
5	0.25	0.30	0.42	0.34	**0.05**
6	0.01	0.01	0.02	0.02	**0.00**

Table: DDS scenario

- In the uniform case, a unique price emerges more often for a 20% increase in production
- In the heterogenous case (production localised in the Northern zones), the two-zonal configuration is more likely, while the configurations with 4,5 and 6 zones are very unlikely

Final remarks

- Our approach provides some relevant advantages in the study of RES impact on wholesale market functioning
- The use of a large amount of detailed data allows to go much deeper into the analysis and to disentangle some important, but often overlooked, effects
- Next steps
  - Simulations
    - Simulating the possible reaction from traditional suppliers (higher bidding prices when RES production runs out)
    - Simulating the effect of investments in transmission links
  - Methodology
    - Improving algorithm's performance by reducing non convergence
    - Further exploring the ranking rules for the feasible solutions

Thank you for your attention!

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