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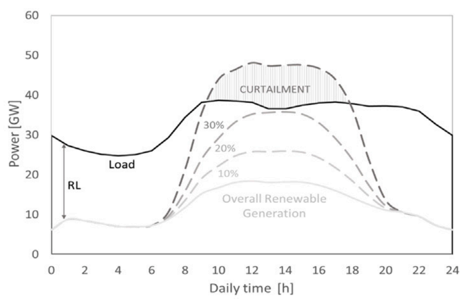
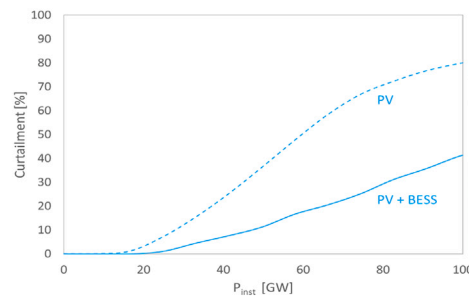
Actual cost of electricity: An economic index to overcome levelized cost of electricity limits

Curtailment of VRES increases with their penetration in the grid and LCOE does not take into account this aspect.

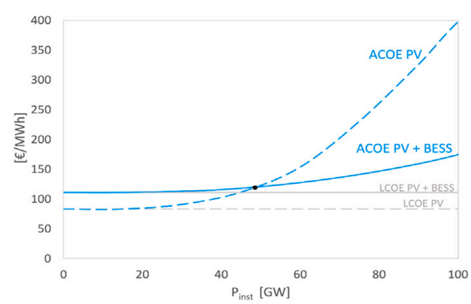




A new index named Actual Cost of Electricity (ACOE) is introduced which accounts for the matching between generation and grid needs.

$$\begin{cases} El_{sold}\,[MWh] = \sum_{i=1}^{8760} \min(El_{pr,i};\ RL_i) = \sum_{i=1}^{8760} \min(P_{inst}\cdot el_{pr,i};\ RL_i) \\ ACOE_{P_{inst}+\Delta P}\left[\frac{\$}{MWh}\right] = \frac{Cost_{P_{inst}+\Delta P} - Cost_{P_{inst}}}{El_{sold,P_{inst}+\Delta P} - El_{sold,P_{inst}}} \end{cases}$$

ACOE exceeding the LCOE by up to 100/150 $/MWh and enables the identification of breakthrough conditions that make storage adoption economically feasible.



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Highlights

A new economic index named ACOE that overcomes the main limit of the LCOE is introduced

Actual cost of electricity (ACOE) accounts for actual electricity demand and curtailment

Additional inputs are the electricity generation and the electricity demand profiles

At VRE penetration around 30%, a 50% discrepancy between the ACOE and the LCOE can occur

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Actual cost of electricity: An economic index to overcome levelized cost of electricity limits

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SUMMARY

The selection of renewable energy technologies is widely based on the economic index levelized cost of electricity (LCOE). However, the LCOE ignores the potential temporal mismatch between electricity generation and actual grid demand: this aspect is accounted for in the new index named actual cost of electricity (ACOE), here proposed. This index provides a more accurate economic assessment of renewable energy, minimizing the number of assumptions to be made and outlining the benefits of including a storage. The proposed index is tested across ten cases encompassing three renewable technologies: wind, photovoltaic, and concentrated solar power. The outcomes show that the actual renewable electricity generation of a plant can be reduced by 40%–50% when accounting for the actual electricity demand, resulting in an ACOE exceeding the LCOE by up to 100/150 $/MWh. In addition, the ACOE enables the identification of breakthrough conditions that make storage adoption economically feasible.

INTRODUCTION

Nowadays, many countries have set ambitious goals to reduce their CO_2 emissions, driving the electricity sector toward an unprecedented deployment of renewable energy.[1,2] In 2018–2022, the worldwide renewable installed capacity has grown by 43%,[3] driven also by a significant technology cost reduction, in particular in terms of capital costs[4] (see Table 1). As a result, photovoltaic (PV) and wind technologies have become competitive with respect to conventional generation technologies as fossil fuel power stations,[4] leading in 2022 to an installation rate equal to 220 GW/y and 100 GW/y for PV and wind, respectively.[3] The economic competitiveness of any power generation technology is usually determined comparing the levelized cost of electricity (LCOE, defined as the price at which the generated electricity should be sold for the system to break even at the end of its lifetime)[4–6] with the actual market price: an LCOE lower than the electricity market price in the considered installation site makes the investment profitable.

LCOE is calculated using only the technology costs and the expected electricity generation over the plant lifetime. It is fundamentally built upon the strong assumption that the value of electricity generated is constant, regardless the time of generation (hour of the day, day of the week, or month of the year).This assumption, which inherently neglects the actual grid demand, is valid as long as the variable renewable energy (VRE) share (aka VRE penetration) in the total production is relatively limited: VREs as wind and PV always have the priority of electricity generation with respect to fossil-fueled power plants due to their lower marginal cost of electricity generation[7] (the marginal cost is set by the operating costs, which for renewable is close to zero as the primary energy source is free). However, when the VRE share is very high or, in the most extreme case, higher than the actual demand, the assumption of constant generated electricity value does not hold, since the electricity generation is likely to be reduced or curtailed. The latter consideration is neglected in the computation of the LCOE.

Curtailment is already occurring in some markets with high VRE penetration. In 2023, the International Energy Agency (IEA) reported an average curtailment of all renewables worldwide around 10%–15% of the potential yearly electricity generation.[3] Moreover, some countries experienced negative prices in 2023 like California,[8] Chile,[9] and South Australia.[10]

Considering that the renewable capacity addition is expected to double every four years[4,11] and that consequently curtailment is expected to increase, LCOE is not the most appropriate index to assess the economic feasibility of a power plant anymore, and a new one shall be adopted.

In literature, several works already proposed innovative approaches to replace LCOE accounting for the actual grid demand together with other relevant aspects as grid stability and required ancillary services[12,13]:

- in 2018, the IEA introduced a new parameter called value-adjusted LCOE (VALCOE)[14] accounting for the World Energy Outlook hourly power supply model and real-world market structures and experience;

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Table 1. Average capital costs and levelized cost of electricity for different renewable technologies installed worldwide (IRENA, 2023)

Technology	Capital cost 2010 ($/kW)	Capital cost 2022 ($/kW)	LCOE 2010 ($/MWh)	LCOE 2022 ($/MWh)
Bioenergy	2,714	2,353	82	67
Geothermal	2,904	3,478	53	56
Hydropower	1,407	2,881	42	61
Solar PV	5,124	876	445	49
Concentrated solar power (CSP)	10,082	4,274	380	118
Onshore wind	2,179	1,274	107	33
Offshore wind	5,217	3,461	197	81

- in 2013, the system LCOE[15] was introduced by Ueckerdt et al. to assess the actual cost on the system of the VREs penetration;
- in 2022, the levelized avoided cost of electricity (LACE)[16] was created for the Annual Energy Outlook published by the US Energy Information Administration;
- in 2022, the levelized full system cost of electricity was presented by Ilen[17] to include in the electricity production costs, investments for the grid improvement, and grid stability issues as firm aspects that are difficult to be predicted;
- in 2015, Zakeri et al. introduced the levelized cost of storage to assess the cost competitiveness of storage systems [18];
- other works [19–21] determined the optimal energy transition through detailed energy models and then recalculated the resulting LCOE on actual electric energy generated.

However, the proposed indexes were not successful in replacing LCOE mainly due to their higher complexity and a significant number of additional inputs required for their evaluation.

Here, we propose a new economic index of the cost of electricity generated, named actual cost of electricity (ACOE), that overcomes the main limit of the LCOE: the ACOE accounts for the matching between the electricity generated by a new installed technology and the actual electricity demand described by the residual load (RL) for the selected location. In contrast to the already proposed indexes, the ACOE can be calculated using accessible information and minimizing the number of assumptions to be made. In addition, this parameter recognizes the value of dispatchability (e.g., programmable or including a storage), an aspect which is not accounted into the conventional LCOE: according to LCOE definition, more expensive technologies with storage as PV plants equipped with battery energy storage systems (BESSs) or concentrated solar power (CSP)[16] are unlikely to compete with PV, whereas this can happen in reality for high PV penetrations, as reflected in the ACOE.

The ACOE can be calculated for any technology, and it is here applied to PV, CSP, and wind as the most relevant technologies, both with and without storage.

The formulation of the ACOE originates from the definition of the LCOE[14] which is reported in Equation 1:

$$LCOE\left[\frac{\$}{MWh}\right] = \frac{Cost}{\sum_t El_{pr,t}\cdot(1+r)^{-t}} = \frac{\sum_t\left(CapEx_t+O\&M_t+Fuel_t+carbon_t+D_t\right)\cdot(1+r)^{-t}}{\sum_t P_{inst}\cdot el_{pr,t}\cdot(1+r)^{-t}} \qquad \text{(Equation 1)}$$

where *Cost* are the overall costs during plant lifetime, El_{pr} is the amount of electricity generated annually in MWh, r is the discount rate, $CapEx_t$ is the total capital cost incurred to build the plant in year t, $O\&M_t$ is the operation and maintenance cost in year t, $Fuel_t$ is the fuel cost in year t, $carbon_t$ is the cost associated with the carbon emissions in year t, and D_t is the decommissioning and waste management costs in year t. The El_{pr} can be calculated as product of the specific technology installed capacity P_{inst} $[MW]$ and its specific electricity production (el_{pr}) [MWh/MW_{inst}].

Since the ACOE accounts for the actual matching between the electricity generation and the concomitant RL on hourly basis, El_{pr} at the denominator of Equation 1 is replaced with the electricity sold to the grid (El_{sold}). El_{sold} is the electricity generated that can be sold to the market as there is an actual need, hence potential curtailment is considered. In the absence of storage, El_{sold} is calculated as reported in Equation 2:

$$El_{sold}\,[MWh] = \sum_{i=1}^{8760}\min\left(El_{pr,i};\ RL_i\right) = \sum_{i=1}^{8760}\min\left(P_{inst}\cdot el_{pr,i};\ RL_i\right) \qquad \text{(Equation 2)}$$

where $El_{pr,i}$ and RL_i are the electricity generation and the actual residual load in the i-th hour of the year, respectively.

Example of the adopted approach for a given day is reported in Figure 1. It can be seen the resulting overall electricity generation for different PV penetrations (between 0 and 30%) and how the curtailment occurs in the central hours of the day.

For technologies that include storage, El_{sold} is computed with the criteria of selling the electricity if it is available in the storage and required by the grid. This is known as *Load Following* approach also adopted in other tools as Homer.[22] More details on the RL_i and El_{sold} calculations in the presence of a storage are reported in the Methods section.

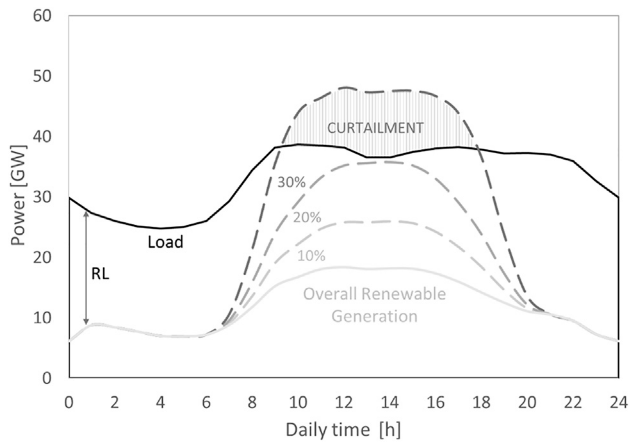

Figure 1. Production profiles for a given day in Italy (15th of May) assuming different percentage of PV penetration

The PV production sums up to the existing renewable generation in Italy. The higher the penetration (three percentages are shown corresponding to 10%, 20% and 30%), the higher the PV generation during the day. For the highest penetration, the overall generation is higher than the load leading to curtailment in the central hours of the day, reducing the electricity generation. RL is the difference between the load and the overall renewable generation on that day (Italy has no nuclear).

Since El_{sold} strongly depends on the installed capacity (P_{inst}) (see Equation 2), ACOE is calculated as the incremental cost to install new capacity (ΔP) divided by the incremental electricity sold as described by Equation 3:

$$ACOE_{P_{inst}+\Delta P}\left[\frac{\$}{MWh}\right] = \frac{Cost_{P_{inst}+\Delta P} - Cost_{P_{inst}}}{El_{sold,P_{inst}+\Delta P} - El_{sold,P_{inst}}} \quad \text{(Equation 3)}$$

This new parameter does not require arbitrary assumptions and can be implemented without accurate prediction of the market evolution (as it is for other indexes as VALCOE[14] or LACE[16]).

The only additional information required with respect to the calculation of the LCOE is the actual RL on hourly basis which can be determined by freely available information from most of transmission system operators. Examples of databases for the energy grid demand are ENTSOE[23] for Europe, ISO[8] for California, or AEMO for Australia.[10] As the ACOE requires the hourly RL as input, it has to be updated on yearly basis as it accounts for the electricity market evolution.

The ACOE calculation can be extended considering two technologies at a time through a parametric analysis; however, this is beyond the scope of this work, which is to introduce the new index and to emphasize its benefits.

RESULTS

ACOE is assessed for ten case studies for PV, CSP, and wind technologies in different countries located in Europe and in North America based on costs and electric demand of 2022. For the wind and PV technologies, the adoption of BESS sized at the 1-h rated power of the plant is also considered. The cases are selected to provide a good overview of the new index with the corresponding benefits: PV is installed in Italy, Spain, France, Germany, and California, wind in Germany, the Netherlands, Denmark, and California, while CSP is considered for California. Each case was selected because it has some peculiarities: for example, California and Spain have high solar radiation, France has a large nuclear presence, and Denmark has already high wind penetration. In general, the interest in the result is not quantitative but qualitative, stressing the importance of overcoming the main limit of the LCOE.

The ACOE depends on the P_{inst} of each technology as per (Equations 2 and 3). A representative graph of the ACOE representing Italian PV case with and without BESS is firstly introduced in Figure 2 to aid in the interpretation of the results.

- the initial ACOE coincides with the corresponding LCOE as for low P_{inst} and El_{sold} coincides with El_{pr} for higher P_{inst}. The ACOE increases as a consequence of the higher curtailment: the higher the installed capacity, the higher is the electricity that can be generated (El_{pr}), but the lower is the electricity share that can be sold (El_{sold});
- the intersection between curves of ACOE with and without BESS defines a value of P_{inst} beyond which the adoption of BESS becomes profitable.

In order to have a unique graph including all the cases, ACOE is plotted vs. VREs penetration, which is the ratio between ($P_{inst} \cdot el_{pr}$) and RL. P_{inst} is the only variable parameter, while el_{pr} and RL are fixed once the technology and the location are defined, respectively. The adoption of VREs penetration as x axis allows extending the analysis to increased RL which can occur because of transport electrification. What matters to calculate ACOE is not the absolute installed capacity, but the relative capacity to the RL.

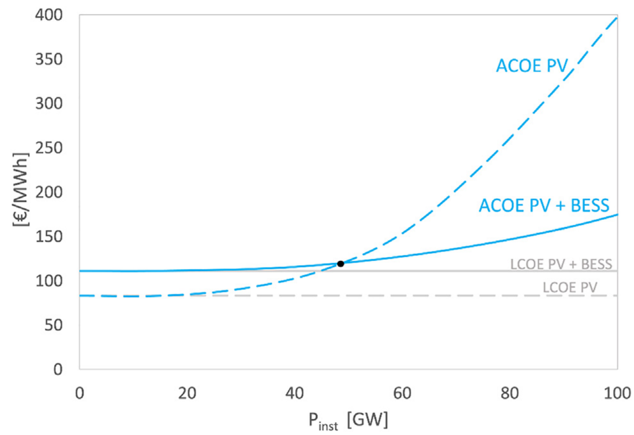

Figure 2. ACOE and LCOE vs. P_{inst} for PV in Italy with and without BESS

P_{inst} is incremental with respect to the installed capacity in 2022. The intersection point shows the P_{inst} at which the ACOE with and without BESS coincides. After this P_{inst}, the configuration with BESS is more competitive from an economic point of view.

ACOE trends for all the considered cases are reported in Figure 3 and the following general remarks can be made:

- ACOE increases with P_{inst}, reaching values 100 €/MWh above the initial one (i.e. LCOE value) as a consequence of the higher curtailment;
- similar trends can be pointed out for cases with the same technology (i.e. PV w/o BESS, PV with BESS, etc.), but they differ from a quantitative point of view because of the different power generation patterns and local electricity demand trends;
- ACOE represents the competitiveness of the technology when it is deployed, accounting also for the initial installed capacity. In addition, it identifies the most profitable technology when in competition as PV and CSP, for each considered installed capacity.

More in detail, the ACOE increases at lower penetration for PV (left) than wind (right) and has a steeper growth. This is due to PV curtailment being more relevant, since generation is strongly concentrated during daylight hours and mostly in summer, while wind is less affected by daily and seasonal patterns due to a more evenly distributed resource. The ACOE of PV with batteries is higher than the corresponding case without batteries for PV penetration equal to 0, but it becomes higher between 25% and 40%, indicating that for higher VREs penetration, the solution with BESS is more convenient. For the wind case, in the considered electric systems, the adoption of a BESS does not allow a reduction of the ACOE. CSP in California, which includes a thermal energy storage (TES) of 8 h, has a significantly higher ACOE for low installed capacity (as a consequence of the higher capital cost), but becomes competitive for VREs penetration around 50% taking advantage of its cheaper storage which strongly reduces curtailment.

To clarify the ACOE trend, Figure 4 plots the corresponding curtailment curves vs. VREs penetration for all the cases.

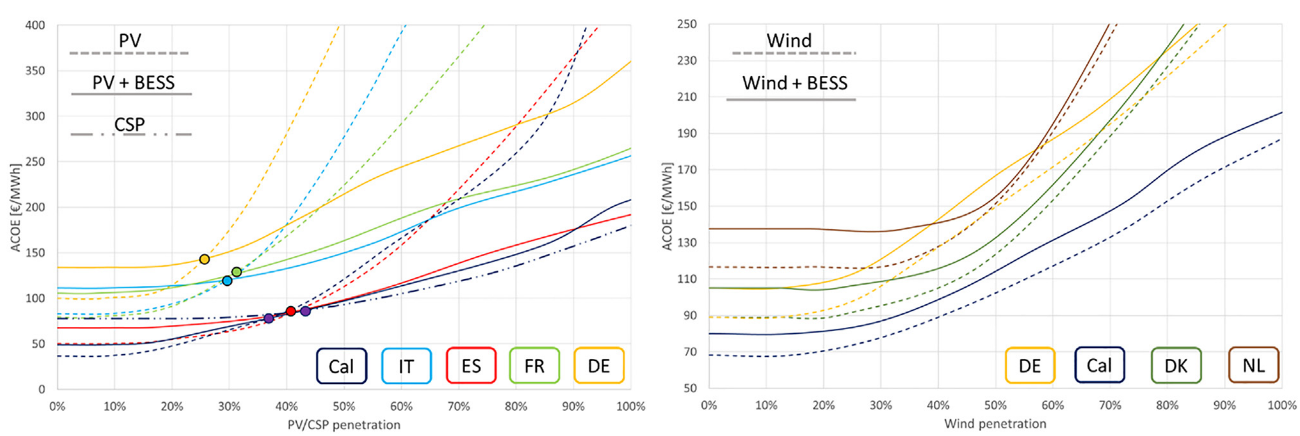

Figure 3. ACOE for PV/CSP (left) and for wind (right) technologies with and without BESS in different electric energy systems

Technology penetration is incremental with respect to the country situation in 2022. The colored circles indicate the VREs penetration at which the ACOE for the given technology with and without BESS coincides. For higher VRE share, ACOE shows the advantages of adopting the BESS mainly for the PV case.

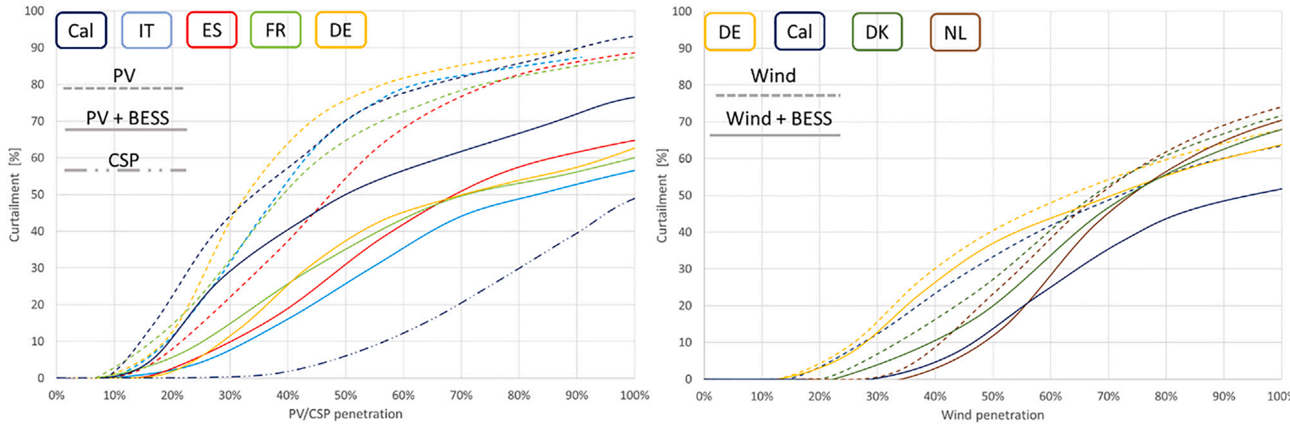

Figure 4. Curtailment for PV/CSP (left) and wind (right) for variable technology penetration in different electric energy systems

Technology penetration is incremental with respect to the country situation in 2022. Benefits of storage can be pointed out in terms of curtailment reduction. CSP, with the highest intrinsic storage capacity (eight equivalent hours of capacity), has the lowest curtailment among solar technologies.

Figure 4 (left) shows that PV curtailment can be high, even with low PV penetration (i.e., California and Germany have a 40% curtailment at only 30% of the VREs penetration). This trend is confirmed by the current situation in California where PV generation is curtailed although the VRE share is below 15%.[8] It can be seen that the curtailment of a PV plant can be strongly reduced by adopting a limited size storage system (i.e., for the Italian case, at VREs penetration equal to 80%, the curtailment reduces from 85% to 50%). CSP (Figure 4 left) has the lowest curtailment due to the use of the TES that enables the decoupling between renewable source availability and electricity generation and/or connection to the grid. The impact of batteries addition on wind technologies curtailment (Figure 4 right) is less relevant due to the more homogeneous resource availability and hence electricity generation.

Finally, the ACOE is reported for the PV case including different storage sizes (from 0 to 2 h) installed in California (see Figure 5). The results show that at higher PV penetration, it is convenient to increase the storage size. Moreover, looking at the graphical representation of the outcomes in Figure 4, it is possible to identify an optimal condition for any given PV penetration.

DISCUSSION

This study proposes a new index for assessing the economic profitability of VRE technologies against their penetration level in the electricity generation system. The most commonly adopted index for economic feasibility is currently the LCOE, which represents the price at which the generated electricity should be sold for the system to breakeven at the end of its lifetime. Its main limitation lies in the fact that it does not account for the matching between the electricity generation and the actual electricity demand, therefore neglecting potential curtailment.

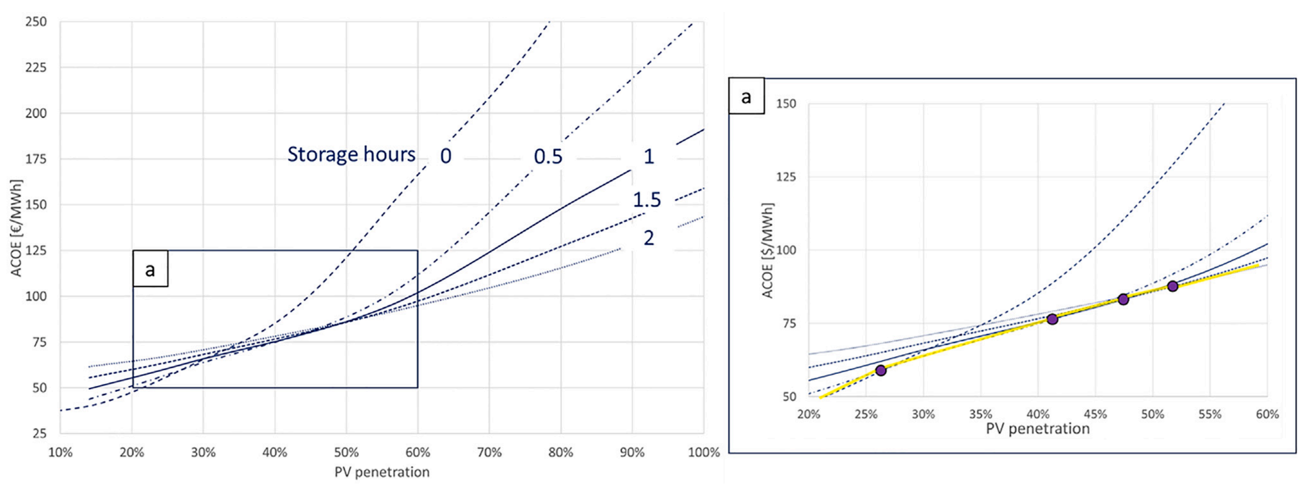

Figure 5. ACOE for the PV case with different storage sizes ranging from zero to two equivalent hours of capacity

On the right, a magnification of the square in the figure on the left, highlighting the intersections between the different curves, and in yellow the optimal design minimizing the ACOE for a given PV penetration.

The adoption of more accurate and updated economic indexes is necessary to properly deal with the increasing deployment of VRE in the grid, resulting in expected higher curtailment.

Several studies in the literature already tried to overcome the LCOE limits proposing new indexes as VALCOE[14] or LACE.[16] However, the proposed indexes did not replace LCOE mainly for their higher complexity and the higher number of inputs required for their evaluation. This work proposes a new index, named ACOE, that accounts for the matching between the generation and the actual electricity demand. The actual electricity demand corresponds to the RL that must be covered by the new installations and it can be determined from hourly grid consumptions available on transmission system operators' websites. This is the only additional input required with respect to LCOE calculation and it has to be determined every year accounting for the RL variation in each country.

The presented results show the relevance of the curtailed electricity on the economic viability of a VRE project, which is well captured by the ACOE, as it strongly depends on the technology installed capacity: higher installed capacity usually corresponds to higher ACOE, reducing the potential economic benefits of renewable energy installation. It can be observed that at VREs penetration corresponding to only 30% of the RL, a 50% discrepancy between the ACOE and the LCOE can occur, since the latter does not acknowledge that not all the electricity generated is useful to cover the actual grid needs (e.g., curtailment of 50% can occur for VREs penetration around 40%–50%). Moreover, this discrepancy can reach 100% for higher VREs penetration, indicating that renewable electricity producers should consider the ACOE when planning future investments. The steep increase of the ACOE for large VREs penetrations shows that Wright's law, in this application, does not hold contradicting previous works.[24,25]

Another advantage of the ACOE is the consistent comparison between technologies with and without storage: assessments based on the LCOE tend to suggest the installation of technologies not equipped with storage systems, penalizing the adoption of batteries and those technologies that are inherently equipped with storage (e.g., CSP). The performed analysis showed that the ACOE enables the identification of a threshold beyond which the adoption of storage is effective from an economic point of view. Moreover, this newly defined index identifies the most economically convenient technology for any range of renewable penetration levels. Although the outcomes may be expectable, they could not be described by the LCOE as the advantages of storing electricity (or potential generation capacity) and selling it when needed by the grid is neglected.

The ACOE provides a preliminary economic evaluation of the electricity generated by renewable technologies, but it is not intended to replace detailed technical design and business plan models of power plant installations. In addition, all the aspects of grid stability and firm capability of the systems are not considered in this index, thus further supporting the requirement of more detailed analyses for accurate energy planning.

Limitations of the study

We proposed a new economic index named ACOE that accounts for actual electricity demand and curtailment, which are not considered in the well-known LCOE. The ACOE can be applied to any electricity generation technology, in this study to renewable energy such as PV, CSP, and wind. This paper demonstrated that accounting for actual electricity demand leads to ACOE significantly higher than LCOE for the same case. The value of the ACOE may be over 150% that of LCOE in some scenarios as it strongly depends on the VRE technology penetration in the chosen market. The ACOE also enables the identification of the technology penetration threshold beyond which the storage system becomes economically convenient.

With respect to the LCOE, the additional inputs required are only the electricity generation and the actual electricity demand profiles on hourly basis for the considered region.

The main limitations of the ACOE parameter and its application presented in this work are here summarized.

- The ACOE is presented for one technology at a time, while multiple technologies are usually deployed. Future works will overcome this limitation.
- In the calculation of the ACOE, both the amount of electricity demand and the hourly distributions are relevant. The electricity demand variation is accounted in the RL, while the modification of the hourly demand is not considered. A different distribution could be considered requiring an arbitrary assumption which is not expected in the ACOE definition.
- The analysis considered few commercial technologies and one storage type/size and did not evaluate emerging ones as seasonal storage. Specific analysis accounting for more technologies will be included in future works.
- Although ACOE has similar trends, each country with corresponding technology has its own peculiarities (i.e., California and Denmark are not necessarily representative of other states and countries); therefore, results cannot be extended, but each case shall be individually treated.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability

- Data and code availability
- METHOD DETAILS
  - ACOE calculation
  - Description of the excel file added to the publication

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109897.

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AUTHOR CONTRIBUTIONS

Conceptualization, G.M., M.B., and M.E.C.; methodology, G.M., M.B., and M.E.C.; software, G.M.; validation, G.M.; investigation, G.G., G.P., and L.P.; formal analysis, G.M., G.G., G.P., and L.P.; writing – original draft, G.M.; writing – review and editing, G.M., M.B., G.G., G.P., L.P., and M.E.C.; visualization, G.M., M.B., G.G., G.P., L.P., and M.E.C.; supervision, G.M. and M.E.C.; project administration, G.M.; funding acquisition, G.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Visual Basic macro MSExcel	MS Excel	https://www.microsoft.com/en-au/microsoft-365/excel

RESOURCE AVAILABILITY

Lead contact

Further information and requests for input data should be directed to and will be fulfilled by the lead contact, Giampaolo Manzolini (Giampaolo.manzolini@polimi.it).

Materials availability

No new data were generated in this research.

Data and code availability

- All data reported in this paper will be shared by the lead contact upon request.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

ACOE calculation

The calculation of ACOE relies on the assessment of the technology costs, the electricity production capacity by a technology and the actual electricity demand of the grid.

ACOE is calculated as reported in Equation 3. For the numerator, costs are determined as:

$$\sum_t \left(CapEx_t + O\&M_t + Fuel_t + carbon_t + D_t\right)\cdot(1+r)^{-t} \quad \text{(Equation 4)}$$

where *CapEx* and *O&M* account for the capital costs and operation and maintenance costs of the different technologies considered, *fuel* and *carbon* costs are zero as PV, wind and CSP do not use any fuel and do not entail CO_2 emissions, and *D* are decommissioning and waste management costs, neglected for simplicity. t is the year at which the expenses occur. For each technology, the capital and O&M costs are determined as reported in the following equations:

$$CapEx_{PV} = C^{PV}_{CapEx} + C^{INV}_{CapEx} + C^{BESS}_{CapEx} \quad \text{(Equation 5)}$$

$$CapEx_{wind} = C^{wind}_{CapEx} + C^{BESS}_{CapEx} \quad \text{(Equation 6)}$$

$$CapEx_{CSP} = C^{SF}_{CapEx} + C^{TES}_{CapEx} + C^{PB}_{CapEx} \quad \text{(Equation 7)}$$

$$O\&M_{PV} = C^{PV}_{O\&M} + C^{BESS}_{O\&M} \quad \text{(Equation 8)}$$

$$O\&M_{wind} = C^{wind}_{O\&M} + C^{BESS}_{O\&M} \quad \text{(Equation 9)}$$

$$O\&M_{CSP} = C^{SF}_{O\&M} + C^{TES}_{O\&M} + C^{PB}_{O\&M} \quad \text{(Equation 10)}$$

Equations 5, 6, 7, 8, 9, and 10 hold for both the case with and without storage, where in the latter case the cost of the storage (BESS for PV and wind) is set equal to zero. The assumptions for the adopted costs are reported in Table S1 with the corresponding reference. We assumed that the cost of each technology is equal for all cases, and it is not affected by the deployment in each state as one state cannot affect the worldwide production. The production costs of each technology (*CapEx*) can be reduced for larger deployment (thus impacting the numerator of Equation 2),[24,25] while OpEx doesn't. In addition, the more deployed the technology is, the lower El_{sold} becomes hence, Wright's law does not hold for the technologies in question.

To assess the costs related to CSP technologies the average between to costs reported in a study by the authors[26] and SAM[27] has been further scaled to align better with a recent publication[28] and an IRENA[4] report that provide cost projections at 2030. The cost assumptions are specific to the considered design, and in general solar field (SF) and thermal energy storage (TES) depend on the selected size. Assumptions on the cost adopted are reported in Table S1

For the denominator of ACOE (see Equation 3), El_{sold} should be calculated as in (Equation 2) using $El_{pr,i}$ and the RL_i. They are needed on hourly basis and as consistent as possible to provide a clear and accurate index.

The $El_{pr,i}$ is calculated as in Equation 11:

$$El_{pr,i} = el_{pr,i} \cdot P_{inst} \quad \text{(Equation 11)}$$

Where $el_{pr,i}$ is the specific electricity production for the considered technology and location and P_{inst} is the considered installed capacity for the selected technology additional to the one already present in the selected location.

The specific electricity production could be obtained through available models (e.g., PVGIS,[29] SAM[27]). However, as the $El_{pr,i}$ shall be as consistent as possible with the RL_i due to the hourly balance, we decided to retrieve the electricity production for the PV and wind technologies from the TSO databases.[8,23,30] Therefore, the $el_{pr,i}$ (kWh/kW$_{inst}$) for the considered area can be properly computed as reported in Equation 12:

$$el_{pr,i} = \frac{El_{TSO,i}}{P_{TSO}} \quad \text{(Equation 12)}$$

Where $El_{TSO,i}$ is the hourly generation and P_{TSO} is the installed capacity for the considered technologies taken from the different national TSO.

A solar tower plant is considered as CSP technology in this work. Since the electricity generation is strongly affected by the presence of storage and it is not decoupled from PV in TSO database (also because of its limited penetration), the production is determined using SAM[27] which is a worldwide adopted tool for CSP modeling (for this case, a Solar Multiple equal to 1.7 and a TES of 8 h are assumed). The cost of the CSP plant corresponds to this specific case.

The RL_i is determined from Transmission System Operators (TSOs) that provides the grid situation on hourly basis with the amount supplied by the different generation technologies.

The following assumptions have been made to facilitate the computation of the RL in each scenario.

- The RL corresponds to the local electricity generation by fossil fuel power stations connected to the grid since those will have to be replaced in the short period to achieve the green energy transition;
- The electricity generation from other existing renewable energy sources (including PV, wind, biomass, hydro) is not considered when assessing the RL since they would be competing with the new VRE installed capacity;
- The nuclear based generation is also neglected when computing the RL. This has been done following the recent European approach [31] that weighs it equally to renewables;
- Once calculated for the considered region for the reference year, the *RL* remains constant for all the VREs penetration investigated. RL has to be updated on yearly basis to account for the electricity market evolution comprising higher renewable penetration as well as higher electricity demand.

Once the $El_{pr,i}$ and the actual RL_i are set, the overall electricity sold (El_{sold}) is obtained as the sum of the single terms on hourly basis (see Equation 2) for the considered installed capacities.

To determine the ACOE, this method is repeated for different installed capacities (P_{inst}+ΔP) assessing the additional El_{sold} and *Cost* necessary for (Equation 3).

When storage options are available with their additional degree of freedom, the rationale of the methodology considers storing the excess electricity (El_{stor}) in the storage (BESS or TES) till the storage is at full capacity, and to release it whenever it is required by the grid. The curtailed energy (El_{curt}) is calculated as described in the algorithm provided in the supplementary material. The model is iteratively applied for the 8760 h of the year and for each of the different installed capacities considered. The flowchart of the developed code to assess the ACOE is reported in Figure S1.

Description of the excel file added to the publication

Input data for assessment of the ACOE in the considered country (electricity demand and electricity generation profiles) are made available through additional material (Data S1). Residual load and specific technology production on hourly basis are reported.