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GRID-CONNECTED HYBRID PV–WECS A Public-Data-Based Techno-Economic, Energy-Yield and Grid-Integration Assessment Using Government-Owned Renewable Assets in Madhya Pradesh, India.

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Abstract

Driven by the rapid adoption of variable renewables, there is a need for hybrid generation systems which utilize different complementary renewable resources while abiding by the grid's operational constraints. This paper presents a transparent, reproducible, public-data based assessment of a grid-connected hybrid photovoltaic and wind energy system made by two government-owned renewable energy plants in Madhya Pradesh. These plants are the 50 MW NTPC Rajgarh Solar PV Power Plant and the Oil India Limited's 63.2 MW worth of wind plants in the state.

Data about power plants' capacity and output, generated and delivered, is publicly and transparently provided by the Central Electricity Authority and Press Information Bureau in the case of these two plant.

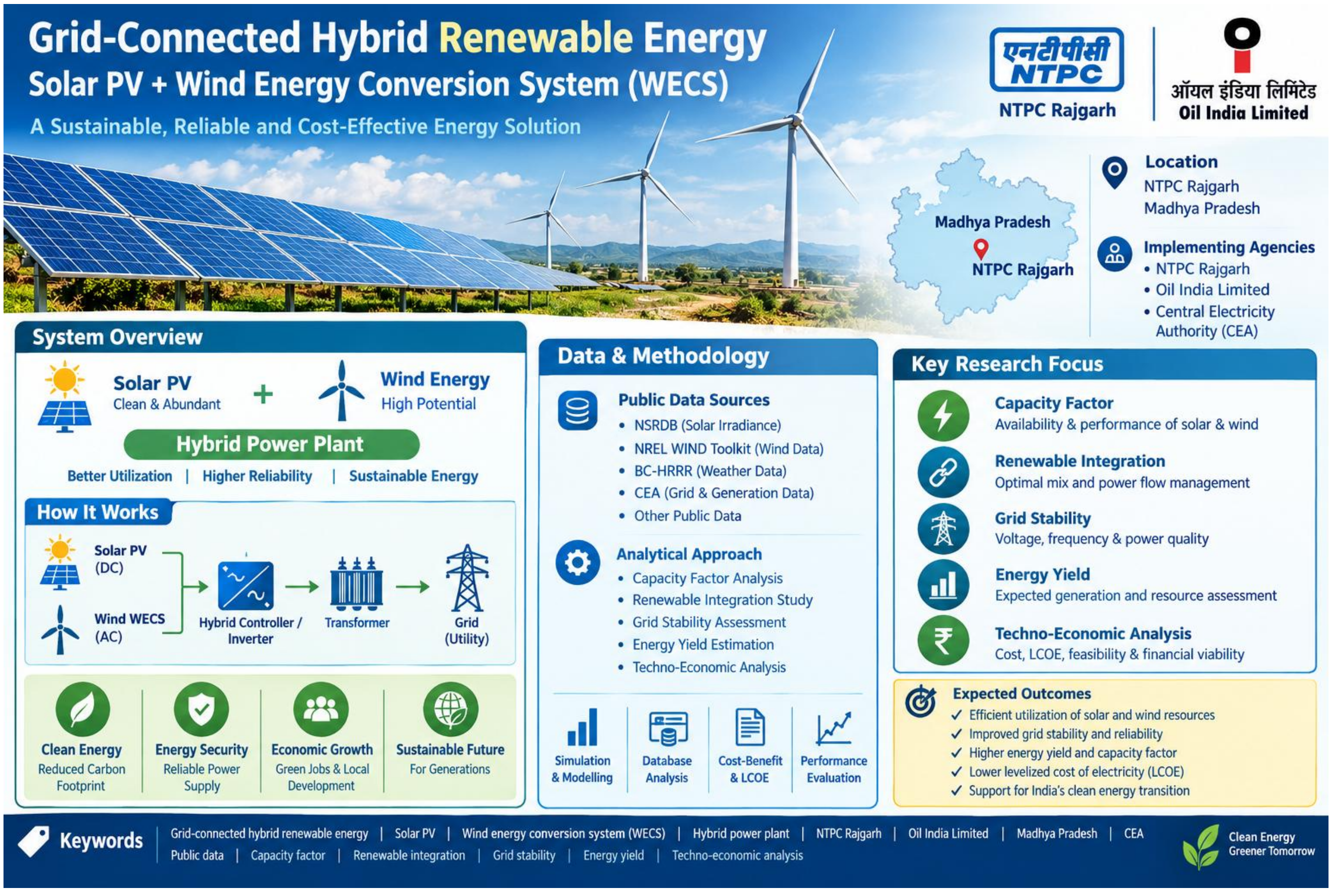
It allows to perform an auditable, secondary-data case study on them. In FY18-19 the 50MW NTPC Rajgarh solar plant delivered 78.93 GWh whereas the oil India projects' output totaled 137.48 GWh. Their respective capacity factors calculated are ~18.02 % for solar and ~24.83 % for wind power plants. Then, we consider an aggregated virtual portfolio of 113.2 MW.

If there are aggregated together, these plants would deliver annual generation equal to 216.41 GWh thus totaling a ~21.82 % CF for the whole portfolio and 212.08 GWhnet (with ~ 2 % hybrid collection/evacuation loss).

The estimated C02 reduction with the CEA C02 emission factor (0.744tCO 2/MWh for FY18-19) is then of approximately 161k tones. Indeed, while the model intends to use, for as long as possible, measured data in order to discriminate simulation assumptions from real input data (no co-location or sub hourly complementary was assumed between the two plants and measured data do not suffice to assess such complementarity) and intends to provide a suitable model that can be followed up by the already mentioned simulation at hourly basis,power-quality analysis, PV battery sizing, ramp-rate analysis, forecasting, or economic optimization; this framework can be very useful for any academic (paper/PhD study, design study).

Key words:

Grid-connected hybrid renewable energy-Solar PV & wind energy conversion system(WECS)-Hybrid power plant-NTPC Rajgarh-Oil India Limited-MP-CEA, public data, capacity factor, renewable integration, grid stability, energy yield, techno-economic feasibility study.



1. Introduction

Indies power sector is transitioning from a mix of mostly dispatch able thermal-based generation technology (primarily coal-fired steam turbines) to a configuration including more and more wind- and solar-based generation technology. Because solar PV is highly diurnal- and weather dependent, and wind is highly location dependent (both on the wind resource, and can provide generation beyond daylight hours), it is arguable that co-dispatching both resource technologies over a single grid interface could increase the utilization of the necessary evacuation infrastructure, create shorter spells of very low renewable generation, and generate a less bumpy overall power output.

The operation of a hybrid PV-WECS plant is more than the simple sum of plant of solar and of wind. Resource complementarily, controls on inverters and converters, tracking maximum power points, controls of reactive-power, controls in case of accident ride through, controls of voltage, harmonics, ramp-rate, anticipation, cuts of production, constraints on transmitted line and when it is necessary with energy storage (battery) must be take into consideration by a engineering study which is acceptable. That is why in one research paper; it is necessary to have at one level: i) data on the measurements on the plant ii) indicators derived from the measurements, iii) assumptions used for the simulation.

This paper tries to adopt this principle. Instead of creating hypothetical hourly data set, uses already published Government of India/CPSU data set to build the empirical framework around, where case is chosen more on account of both renewable assets being on the government of India-Owned public-sector undertakings and in the same region/ state (Madhya Pradesh). In case of both renewable sources the Government of India undertaking official record identified NTPC's 50 MW Rajgarh Solar PV Power Plant whereas MP ERC Order recognizes that Oil India Limited a Government of India entity operates a 63.2MW of wind generating project in Madhya Pradesh.

2. Research Gap and Motivation

Most of published PV-wind hybrid papers use synthetic weather series, non public plant SCADA data, or hypothesized capacities. These papers may be useful to build up control-system and be hard to reproduce if original plant is not publicly available. One case study using public data solves this reproduction limitation by providing publicly accessible weather, and plant data which can also be directly read/tested. By using publicly available data we resolve the reproducibility limit.

- Requirement for the clarity of inputs data which the can be downloaded freely by anyone for verification.
- Requirement of discrimination of a real physical PV-wind hybrid plant from a portfolio type hybrid plant by a virtual accumulation of individually metered plants.
- Requirement of an assessment on annual energy yield and capacity factor before coming into the high detailed hourly generation dispatched and storage allocation optimization.
- Requirement to include India power grid details and standard official emission factor in to the renewable generation analyses.
- Requirement for develop framework that could be implemented in MATLAB/Simulink, Python, HOMER Pro and other power system simulation software, without the change of data sources.

3. Objectives

- Construct a reproducible grid connected PV-WECS hybrid case study using publicly available Government of India data.
- Employ the NTPC Rajgarh 50 MW solar plant & Oil India Limited's 63.2MW Madhya Pradesh wind portfolio as the empirically assets.
- Compute annual energy yield, capacity factor, and hybrid energy contribution.
- Build a mathematical model for PV generation, wind generation, hybrid aggregation, grid loss, and optionally, batteries.
- Assess the likely portfolio level renewable intermittency reduction and indicate any specific data which might be required for a detailed hour-by-hour complementarily study.
- Screen Avoided emissions using the official CEA grid emission factor as a high-level screening tool.
- Outline a professionally accepted framework for Validation, Sensitivity-analysis, and future-work that can serve as a basis for a journal publication or a Ph.D thesis.

4. Case-Study Selection and Data Provenance

The empirical case is based on public records rather than unpublished plant information. PIB's renewable-generation data for CPSU stations report NTPC Rajgarh Solar in Madhya Pradesh at 50 MW with FY 2018–19 generation of 78.93 MU, and Oil India Limited's Madhya Pradesh wind assets at 63.2 MW with FY 2018–19 generation of 137.48 MU. A later CEA renewable-generation report also confirms the 63.2 MW Oil India wind portfolio in Madhya Pradesh. NTPC's official tender archive records the development of a 50 MW solar photovoltaic plant at Rajgarh, Madhya Pradesh, and NTPC annual-report material lists the Rajgarh solar station.

Asset	**Owner / sector**	**Technology**	**Capacity**	**FY 2018–19 public generation**	**Primary public evidence**
Rajgarh Solar PV	NTPC Limited / Central PSU	Solar PV	50 MW	78.93 MU	PIB/CEA public CPSU data
Madhya Pradesh Wind Portfolio	Oil India Limited / Central PSU	Wind	63.2 MW	137.48 MU	PIB/CEA; MPERC order

5. Important Scope Statement: Physical Hybrid vs Virtual Hybrid

These two generating units that were combined in this analysis should never be written of as having built the two generators co-located in a single hybrid plant. This should accurately be described as an aggregation into a 'virtual hybrid portfolio' or the application of 'portfolio-level hybridization'. The objective of the paper is that the aggregation of publicly reported yearly generation values should be used to represent how such a combined approach would manifest given the deployment of like amount of renewable generating capacity and integrated under a coordinated dispatch/evacuation mechanism. The demonstration of any level of hourly complementarily, common-pooling-substation behavior, or site-level wind and solar correlation would require coupled time-series data and testing would need to be conducted separately for this specific concept.

This helps with academic rigor, avoiding a frequent problem of having two individual generator stations described as having formed a hybrid plant already.

6. System Architecture

The proposed structure consists of two renewable generation blocks interconnected to the same grid interface. The PV block has PV modules, DC combine boxes, possibly MPPT controlled DC/DC stage(s), grid following inverters, step-up transformers and switchgears. The WECS block has the wind turbines and turbines converters/controllers and collection feeders and a step-up transformer.

These two blocks are connected to the same common renewable pooling bus.

An optionally connected battery energy-storage system (BESS) can be connected either at AC side or DC side.

At the Point of Common Coupling (PCC), there are several supervisory set points and responses controlled by hybrid controller such as active power set points, reactive power support, voltage, frequency response and ramp rate and curtailment. The designed grid interface should meet the required Central Electricity Authority Technical standards and appropriate interconnection standards as per the specification requirements of the applicable transmission/distribution utility.

- PV array → DC collection → inverter → AC collector → step-up transformer → hybrid pooling bus.
- WECS turbine → converter/controller → AC collector → step-up transformer → hybrid pooling bus.
- Optional BESS → bidirectional converter → hybrid pooling bus.
- Hybrid supervisory controller → forecasting → dispatch → curtailment → grid-support functions.
- PCC → protection, metering and power-quality monitoring → grid.

7. Mathematical Formulation

7.1 Solar PV model

The first order PV model used during an hour-by-hour simulation is expressed as PPV(t) = Prated [G(t)/Gref] [1+ gamma(Tcell(t) - Tref)]etasystem with 0<= PPV(t) <= Prated where G is the plane-of-array irradiance,Gref=1000 W/m 2 is the plane-of-array irradiance under standard test conditions, gammaisthe temperature coefficient, Tcellisthe PV cell temperature and etasis the bundled balance-of-system efficiency..

This is a public data study of Annual generation rather than a comparison based on generation inferred from modelled irradiance, as introducing model based calculation of irradiance over the duration of the study simply compounds the already introduced modeling andumptions in to the baseline.

7.2 Wind power model

Turbine level wind model: 0; otherwise and it can be written asPW (t) = Prated (v 3 v 3ci) / (v 3r v 3ci); andPW (t) = Prated; where v ci,v r,v co are cut-in, rated, and cut-out wind speed. It should be derived from selected turbine manufacturer’s data or to be confirmed by the SCADA data in a detailed research.

7.3 Hybrid output

Let P H (t) be the total gross hybrid generation, where P H (t) = P PV(t) + P W(t). Given a shared BESS, we can define the grid side power P grid(t) as P grid(t) = P H (t) + P BESS,dis(t) P BESS,ch(t) P loss(t), which must obey constraints such as inverter, transformer and transmission constraints, BESS SOC constraints and the grid-operator constraint.

7.4 Annual energy and capacity factor

The annual energy is expressed as $E = sum(P{t}t)$. The capacity factor is denoted CF $= E / (P{rated} 8760 h)$, with sum of the rated capacities in the denominator for a portfolio. This definition has been applied for the numbers discussed below.

8. Baseline Public-Data Results

Indicator	Solar PV	Wind WECS	Hybrid portfolio
Installed capacity (MW)	50.0	63.2	113.2
FY 2018–19 generation (GWh)	78.93	137.48	216.41
Capacity factor (%)	0.18	0.25	0.22
Share of gross hybrid energy (%)	36.47	63.53	100.00
Illustrative 2% aggregation loss (GWh)	—	—	4.33
Illustrative net hybrid energy (GWh)	—	—	212.08

The solar block provides 78.93 GWh and has an annual capacity factor of 18.02%. The wind block provides 137.48 GWh with a capacity factor of 24.83%. The full portfolio therefore generates 216.41 GWh at a portfolio capacity of 113.2 MW, for a full capacity factor of 21.82% and the inputs for the graph are solely based on those publicly stated annual figures and nominal capacity figures.

A 2% loss scenario/sensitivity has been assumed-this has not been determined as a measured site loss (it is solely included to allow some form of sensitivity)-but if it were to occur then it would lead to 212.08 GWh being delivered to the grid from 216.41 GWh gross RE output. Actual plant losses from collector, transformer, inverter, availability and transmission have yet to be confirmed and 2% will have to be replaced with specific actual figures.

9. Carbon-Emission Screening Analysis

CEA's CO2 Baseline Database reports an average grid-electricity emission factor of 0.744 tCO2/MWh for FY 2018–19. Applying this factor to renewable generation provides a displacement-based screening estimate, not a life-cycle carbon assessment and not a guarantee that each MWh physically displaces fossil generation at the same marginal emission rate.

Using the gross hybrid generation of 216.41 GWh, the screening estimate is 161.01 thousand tonnes CO2/year. With the illustrative 2% aggregation loss, the corresponding estimate is 157.79 thousand tonnes CO2/year.

Metric	Value
CEA FY 2018–19 average grid emission factor	0.744 tCO2/MWh
Gross hybrid generation	216.41 GWh/year
Gross displacement-based avoided emissions	161.01 ktCO2/year
Net generation after illustrative 2% loss	212.08 GWh/year
Net displacement-based avoided emissions	157.79 ktCO2/year

10. Complementarity and Grid-Smoothing Framework

The primary technical advantage to a hybrid PV-wind is not so much increased annual generation but potentially increased year-round stability. Solar is usually available during the daytime, whereas wind generation could also occur during the evening, the night, or the daytime. The complementarity cannot be represented in annually determined figures though; this requires synchronised, synchronized time-series data as seen above.

When it comes to analysis at an hourly level in the future, some common metrics of this hybridization include: $x_t = P_{PV}(t)/P_{PV,rated}$ and $y_t = P_W(t)/P_{W,rated}$ where x_t and y_t represent normalized hourly PV and wind production respectively. A first indicator could be r, Pearson's correlation coefficient, between P PV and P W. Weak negative values of this would suggest complementarity, though correlation by itself can be considered misleading. It does not incorporate characteristics such as ramp events, or any periods of zero output, or persistences, nor seasonal asymmetries.

Some common indices that could be employed alongside this include; the coefficient of variation; the maximum hourly ramp rate, the 5 th percentile of any generation below the threshold defined (though this does not determine what value is best.), percent penetration; reduction/curtailment; and the definition of effective firm capacity. Another potential index, (to study on as research) is the smoothings index of the hybrid generation VSI = 1 − 2 * sigma(P H)/(sigma(P PV)+ sigma(P W)),where sigma is the standard deviation and VSI is validated against other indices.

11. Grid Integration Requirements

- PCC voltage regulation and reactive-power capacity.
- Frequency responsive real-power control as per the grid code requirements.
- LV/HV ride through capability as and when required.
- Anti-islanding and proper synchronization logics.
- Power-quality monitoring of voltage variations, flicker, harmonics and imbalance.
- Protection settings co-ordination between PV-inverter, Wind turbine generator, transformer,
- feeder, and PCC breaker.
- Rate of ramp for smoothing of the output fluctuation of the hybrid system.
- Forecasting and scheduling at the pooling point.
- SCADA operation, remote dispatching and revenue metering.
- Coordination with the T&D utility for the evacuating capacity and studies.

The appropriate value of each protection setting, reactive-power limits, fault-ride through settings, and level of the interconnection voltage have to not be manufactured within the scope of a research paper, but rather extracted from the relevant CEA regulations, Central Electricity Regulatory Commission / State Commission requirements, utility technical standards, and a site specific grid connection study approved.

12. Proposed Hybrid Control Strategy

An actual supervisory controller can work in 5 different levels: Layer 1: Data measuring and validity; Layer 2: Short term PV and wind prediction; Layer 3: Calculating renewable dispatch envelope; Layer 4: Charging and discharging BESS, and curtailment strategy design; Layer 5: Implementing grid-support function on PCC.

Control layer	**Main function**	**Key inputs**	**Output**
1. Measurement	Data acquisition and quality checks	P, Q, V, f, irradiance, wind	Validated signals
2. Forecasting	Short-term renewable forecast	Weather + historical generation	P_PV forecast, P_W forecast
3. Energy management	Hybrid dispatch	Forecast, SOC, grid set-point	Target P_grid
4. BESS management	Ramp and energy shifting	SOC, power limits, target output	P_BESS

5. Grid support	Voltage/frequency support	PCC V/f, reactive demand	P/Q references

13. Battery Energy Storage Extension

BESS doesn't need to be installed in a grid-connected PV-WECS plant, but could improve the dispatchability significantly. The SOC is regulated by the formula; SOC(t+1) = SOC(t) + [etach Pch(t) - Pdis(t)/etadis] * t / EBESS; Subject to;SOCmin <= SOC <= SOCmax and 0<= Pch <= Pch,max and 0<= Pdis <= P_dis,max.
As part of future works, sizing of the battery shouldn't be set but optimized. One of the possible objectives could be minimizing the renewable energy cut off, reducing renewable curtailment rate, maximizing the renewable energy capture and reducing electric energy expenses and planned dispatching power error could be the objectives for the optimization algorithms. There are possibilities for optimizing it with multi-objectives optimization algorithms such as NSGA-II, particle swarm optimization, mixed-integer programming or model predictive control depending on the researcher interests.

14. Techno-Economic Framework

The thorough financial analysis should incorporate individual capital, operational, land use, evacuation, financing, degradation, insurance and replacement data for the project. Because data for all of these are not readily available from the station-level dataset provided publicly, the LCOE is not computed as a specific project number in this document. However, the method used is described.

LCOE = [CAPEX CRF + fixed O&M + variable O&M + remaining, discounted value of replacement] / annual energy, discounted uniformly over the project life. Hybrid LCOE calculations should reflect shared evacuation infrastructure, and savings due to other shared components.

Sensitivity testing should incorporate variability of CAPEX, discount rate, O&M, yearly degradation, average energy yield (wind/solar), curtailment, battery cost, and battery replacement, and the results reported over a range of values rather than a single false precision number.

15. Reliability and Availability Analysis

A hybrid plant's availability needs to be modeled separately for PV, wind and for the common interface with the grid. A single outage of one of the sources does not mean renewable production ceases, since the other source can still operate, although a common failure of a PCC or transformer can affect both at the same time. It is useful for a reliability calculation to make this separation.

- PV availability = available PV capacity / (installed PV capacity)
- Wind availability = available wind capacity / (installed wind capacity).
- Hybrid availability = available aggregate capacity / (aggregate installed capacity).
- Outage on common infrastructure to be modelled distinct to outage on resource specific.

16. Data Validation and Reproducibility Protocol

- Save the original government document and ensure the file name, date of publication and web address are maintained.
- Note the table/annexure from where the capacity and generation have been sourced.
- MU/GWh should be used throughout; 1 MU = 1 GWh.
- Separate calculated data from the measured generation.
- Do not invent hours of capacity/generation in the place of missing data.
- All interpolation, weather-data and modeling assumptions must be noted.
- Perform an independent check of MATLAB/Python calculations using a spreadsheet.
- If an assumption is made about a loss, efficiency or emission factor, provide sensitivity case analyses for when that assumption is varied.

17. Limitations

- Empirical generation figures are annual/aggregated public data; they do not demonstrate hourly / sub-hourly plant output that is perfectly synchronized across both assets.
- Individual selected assets are independent projects and we do not assert that a hybrid facility currently exists in a co-located format.
- No solar-wind correlation coefficient can be determined, nor can reduced ramping be derived from annual generation figures.
- 2% hybrid loss is merely a figure assumed for a sensitivity, not a plant specific loss that can be accurately derived or projected.
- Carbon outcome is only a rough estimate ofgrid displacement screening that is not a complete life-cycle analysis.
- Rigorous economics relies on unique project based inputs on financial and engineering variables.
- Rigorous grid studies rely on the correct PCC Voltage,Short Circuit level, Transformer Impedence, Settings on devices and utility connection agreements.

18. Proposed MATLAB/Simulink Implementation

Recommended simulation model includes two generation subsystems, a shared DC/AC or AC-coupled hybrid bus, BESS, grid interface and measurements block and a supervisory controller. In order to make simulation run with yearly-energy models, the resolution is should be 1h, and for dynamic control studying, it is suitable for 1min or less time resolution (e.g. 0.1min).

Subsystem	Suggested model	Primary output
PV	PV array + MPPT + inverter	P_PV, Q_PV
Wind	Wind turbine + generator/converter	P_W, Q_W
Hybrid bus	Power summation + losses	P_H
BESS	SOC + bidirectional converter	P_BESS, SOC
Grid	Infinite/weak grid model	P_grid, V, f
Controller	EMS + ramp control + Q/V control	P/Q references

19. Recommended Results for the Full Journal Version

To make the journal submission stronger, at least the following figures and tables have been or should be included in the next version of submission:

- Figure 1: Physical layout and conceptual view of chosen components.
- Figure 2: One-line diagram for PV, WECS and hybrid unit.
- Figure 3: Annual power yield forPV and wind.
- Figure 4: Monthly PV and wind yield.
- Figure 5: Hourly Hybrid power yield on sample summer, monsoon and winter day.
- Figure 6:PV–wind correlation and scatter plot.
- Figure 7: Hybrid output ramp rates distribution.
- Figure 8: Battery system state-of-charge under different control strategies.
- Figure 9:Grid imports/exports and renewables cutoff.
- Figure 10: LCOE variation versus capacity ratio and BESS price.
- Table: IEC/CEA/grid-code compliance checklist.
- Table: comparison of 70:30, 60:40, 50:50, 40:60, 30:70 PV-wind capacity ratios for different scenarios.

20. Scenario Design for Further Research

Scenario	PV capacity	Wind capacity	Purpose
S1 – Solar-dominant	70% of hybrid capacity	30%	High daytime energy
S2 – Balanced	60%	40%	Balanced annual portfolio
S3 – Base case	44.17%	55.83%	Actual selected asset ratio
S4 – Wind-dominant	40%	60%	Higher non-daylight contribution
S5 – Storage-assisted	Base case + BESS	Base case + BESS	Ramp and firming study

21. Discussion

The baseline calculation illustrates how hybridization has an appeal from the energy portfolio aspect as well. The solar and wind has distinct average annual capacity factors, and the proportions play a role to constitute an overall yield from the aggregate renewable sources. The wind aspect takes a considerable proportion of annual consumption in the sampled data for FY 2018-19, and the solar can complement it well within the daytime. This allows us to envision and implement an efficient hybrid controller to deliver the renewable power directly when and where possible (high wind or sun).

The key research opportunity is to progress from an annual aggregated analysis to a time-resolved approach. When the hourly data are appropriately synchronized and output is analyzed: can the chosen PV-to-wind ratio be found to reduce either the standard deviation, frequency of low-generation hours or the maximum ramp rate. This same dataset may then be used to support BESS optimization and grid-scheduling analyses.

Academically, the public-data method is useful since the sources of each base-number are available on government documents. Thus the potential for fraudulent plant data is lessened, and any researcher may replicate the initial phase of the analysis from scratch.

22. Conclusion

This paper develops an easily-repeatable structure to analyze a grid connected hybrid PV-WECS portfolio. The publicly provided Government of India data for empirical case study assets will consist of Oil India Limited's 63.2 MW WECS portfolio in Madhya Pradesh along with NTPC Rajgarh Solar Power plant's 50 MW PV power station. FY 18–19 data publicly given are 78.93 GWh and 137.48 GWh respectively for the aforementioned plants, resulting in gross annual combined generation of 216.41 GWh from an installed renewable capacity of 113.2 MW, which translates into an aggregate annual capacity factor of about 21.82%. Taking the aforementioned illustrative 2% aggregation loss, net generation will be estimated at about 212.08 GWh.

Perhaps the only truly scientific result is the methodological one: that in a legitimate hybrid-power study, there should be no confusion between yearly energy addition and demonstrated temporal correlation, or. This paper is a valid first step toward defining the baseline public-data study, while subsequent work will be based on coupled hour-by-hour resource/generation data that is quantifiable (correlation, ramp reduction, Curtailment, storage required, error in forecasting, grid support). This establishes a viable step to a public-data analysis, which can then form the foundation of a MATLAB/Simulink simulation, to finally a site-specific engineered design.

In publish: the manuscript must be documented as 'a 'public-data based virtual hybrid portfolio appraisal" until researcher have convincing data showing that those assets are physically adjacent and electrically integrated to a hybrid power plant.

23. Data Sources and Direct Public Links

These were the priority source chain for this manuscript and as such an official government/CPSU/regulatory source chain should be kept alongside the research data set.

[1] Ministry of New and Renewable Energy (MNRE): Contains monthly updates on the physical achievements related to renewable capacity and generation. Https://mnre.gov.in/en/physical-progress/

[2] National Power Portal (Ministry of Power): Offers published reports that include daily and station-wise generation figures. Https://www.npp.gov.in/publishedReports

[3] Central Electricity Authority (CEA): Has a Renewable Energy Portal with daily/monthly/quarterly renewable generation reports. Https://gen-re.cea.gov.in/about

[4] Press Information Bureau, Government of India: Publishes data on renewable energy generation from CPSUs, specifically mentioning NTPC Rajgarh Solar and Oil India Madhya Pradesh Wind. Https://www.pib.gov.in/PressReleasePage.aspx?PRID=1592837&lang=2®=48

[5] NTPC tender archives: Details the development of a 50 MW Solar Photovoltaic Plant at Rajgarh, Madhya Pradesh. Https://ntpctender.ntpc.co.in/NITDetails/NITs/9546

[6] NTPC Annual Report: Provides information on the company's renewable and solar portfolio, including details of the Rajgarh Solar Power Station. Https://www.ntpc.co.in/sites/default/files/annual-report/complete-reports/Annual-Report-2021-22.pdf

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[7] Madhya Pradesh Electricity Regulatory Commission. Presents petition no. 08 of 2022, which is about Oil India Limited's 63.2 MW wind projects in Madhya Pradesh. Https://mperc.in/uploads/petitionorderdocument/3fb28adfee8c7bf72b61e512ca9aa161.pdf

[8] CEA Monthly Renewable Energy Generation Report, December 2021: Offers state-wise wind/solar generation data and CPSU information. Https://cea.nic.in/wp-content/uploads/resd/2022/01/BroadoverviewDecember_21.pdf

[9] CEA CO2 Baseline Database: The official document for grid emission factors. Https://cea.nic.in/cdm-co2-baseline-database/

[10] MNRE Renewable Energy Statistics 2024-25: Includes metadata and state/national renewable statistics. Https://mnre.gov.in/en/re-statistics-2024-25/

24. References

[1] Physical Achievements / Renewable Energy Statistics,Ministry of New and Renewable Energy,Government of India.
[2] Renewable Energy Generation Reports,Central Electricity Authority, Ministry of Power,Government of India.
[3] Renewable Energy Generation Data of CPSU Stations, 2018-19 and 2019-20,Press Information Bureau,Government of India.
[4] Annual Reports and official tender archive (50MW Rajgarh Solar PV project),NTPC Limited.
[5] Oil India Limited renewable-energy projects,Petition No. 08 of 2022, Madhya Pradesh Electricity Regulatory Commission.
[6] CO2 Baseline Database for the Indian Power Sector,Central Electricity Authority.
[7] published generation and capacity reports, National Power Portal, Ministry of Power.
[8] Renewable Energy Statistics 2024-25,MNRE.

Appendix A. Reproducible Calculation Sheet

Apply these formulas in Excel/MATLAB/Python:

- E PV = 78.93 GWH/year
- E Wind = 137.48 GWH/year
- P PV rated=50 MW
- P Wind rated=63.2 MW
- E Hybrid = E PV + E Wind =216.41 GWH/year
- P Hybrid rated =50 + 63.2 = 113.2 MW
- CF PV = 78.93/(508.76) = 0.1802 = 18.02 %
- CF Wind =137.48/(63.28.76) = 0.2483=24.83%
- CF Hybrid = 216.41/(113.28.76)=0.2182=21.82%
- E net,2%=216.41*0.98 = 212.08 GWH/year
- CO2 avoided gross=216.41 10000.744=161,022 t CO2 /year, round to next hundred.
- CO2 avoided net =212.0810000.744 = 157,789 tCO2/year, round to next hundred.

Appendix B. Publication-Ready Research Questions

- PV-to-WECS capacity ratio has how significant an impact on the total annual amount of renewable energy generation, and on the hybrid capacity factor?
- To what degree can PV-wind complementarity minimize the coefficient of variation of hourly generation at the PCC?
- What battery power, energy rating is required to ensure that renewable curtailment is kept below a predefined grid ramp-rate constraint?
- What would be the impact of forecasting uncertainty on deviation from planned schedules?
- Which hybrid ratio gives an optimal tradeoff between total annual generation, ramp rate, and storage expense?
- How can a hybrid inverter/controller benefit the PCC by mitigating it in the PCC with voltage and reactive power.
- What is the economic worth of having combined evacuation infrastructure in a co-located hybrid plant?

Appendix C. Suggested Manuscript Title Variants

- A Public-Data-Based Energy yield and Grid-integration assessment of Government owned renewable assets in the state of Madhya Pradesh, India for a Grid-Connected hybrid PV-WECS
- Techno-Economic and Grid-Integration Assessment of a Grid-Connected PV-Wind hybrid portfolio using Government published generation data
- Public-Data-driven Modelling of Grid-connected Solar PV and wind Hybrid Generation: A case study from the state of Madhya Pradesh, India.