

# An Energy-Mix Model for Round-the-Clock Power Supply in a Decarbonized Electricity Generation Scenario: Case Study of South India

Ankit Kumar

Indian Institute of Technology Madras

Sreenivas Jayanti (✉ [sjayanti@iitm.ac.in](mailto:sjayanti@iitm.ac.in))

Indian Institute of Technology Madras <https://orcid.org/0000-0001-8929-1980>

---

## Research Article

**Keywords:** Renewable energy sources, Decarbonization policies, Energy mix, Energy Storage, Integration of renewable energy sources, Supply-demand management, Transmission and distribution losses

**Posted Date:** July 27th, 2022

**DOI:** <https://doi.org/10.21203/rs.3.rs-1616363/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

---

# Abstract

There is increasing urgency towards integration of renewable sources into electricity generation so as to minimize greenhouse gas (GHG) emissions. Renewable power sources are highly specific in prevalence, both regionally and temporally, and their utilization at utility-scale for round-the-clock power supply poses the problem of matching power generation capacity and power demand at every instant of time. In the present work, we propose a model that integrates geographically distributed and diverse power sources with geographically spread-out power consumption centres and distributed and diverse electrical energy storage systems through transmission and storage loss models. For a regional electricity grid, the model computes, over a given day, the minute-by-minute power demand from and power generation in all districts, extracts matching power from a hierarchy of power sources so as to minimize transmission and storage losses, and stores/draws excess power in/from a variety of power storage options. For the specific case of the South Indian Power Grid (catering to about 285 million people in South India), the model shows that about 240 GWh of new electrical storage is required for round-the-clock power supply from non-GHG power sources.

## 1. Introduction

With the rapid growth of electricity generated by renewable power sources, especially solar photovoltaic (PV) and wind, both of which are highly variable and intermittent, attaining CO<sub>2</sub>-neutral power generation (which is achieved only if the CO<sub>2</sub> generated from manufacturing and operation of renewable generation is offset by carbon removal) at utility level appears to be both a tantalizing prospect and a formidable challenge. When renewable energy sources (RES) account for a large portion of the power supply, their inconstant availability presents challenges to power grid service, leading to RES curtail and loss of efficiency of thermal power plants, which then are often operated at part-load as changing back-up power. Barelli et al. (2015) examined this factor in depth in relation to the Italian electricity generation mix from 2008 to 2012, and noted that the function of thermoelectric plants, in particular, had moved from base-load to fluctuating backup capacity. The main consequence was an increase in both energy consumption and wear-and-tear costs as a result of lower performance service. Tarroja et al. (2012) have produced metrics to assess the impact of intermittent renewable generation on the electric load demand that must be balanced by dispatchable generation resources, allowing for a more thorough analysis of the overall effects of allowing high renewable penetration levels. The metrics are concerned with the sizing, allocation, and alignment of load balancing services in order to meet load demand in a timely manner. For the state of California, they found that at high penetration rate of RES, the balancing generator fleet had low power factors. Surplus generation occurred at penetration rate above 45% with no uninterruptible base load. Set time-of-use electricity pricing became ineffective as the frequency of regular maximum and minimum load points became increasingly unpredictable.

Flores et al. (2016) examined the issue of how to choose electricity generating technologies for a decentralized energy generation system based on local renewable sources in a developing country's rural area (six municipalities in Western Honduras). Rather than constructing a high-reliability electricity

generation system with high-quality power, the goal of this work was to give the fundamental configuration of an energy mix for a rural area with low-resolution energy data. The technologies were chosen using a non-linear integer programming methodology that aimed to reduce the levelized cost of power (LCOE). The model takes as inputs, data on energy resources, conversion technologies, the Honduran economic framework, the research area's electricity demand, and the cost of energy storage. Solar photovoltaics, wind turbines, biomass direct combustion with a steam turbine, and biomass gasification with a gas engine are among the energy resources evaluated, while electricity generation technologies considered include solar photovoltaics, wind turbines, biomass direct combustion with a steam turbine, and biomass gasification with a gas engine. As functions of electricity capacity, three case studies were proposed: off-grid, mini-grid, and grid-connected. The model outputs for each case study include the electricity supply share for each technology, the LCOE, and the number of power plants with the relevant power capacity needed to meet the study area's electricity demand. This work might be used as a starting point for early feasibility evaluations of renewable energy electrification projects in other rural areas of Honduras or other developing countries.

Ray et al. (2018) examined the possibility of hybridization of locally available diverse renewable resources to deal with intermittency of these resources. A multi-criteria optimization using cuckoo search algorithm for simultaneous best combination of economy, land use and greenhouse gas (GHG) emission was carried out for polygeneration with three utility outputs, namely, electricity, heat and high calorific value gas. Using data for a small hilly village of India with mostly poor people, they found the levelized cost of electricity at 100% reliability of power supply to be 0.1 USD/kWh. Dawoud (2021) studied the possibility of energy supply to the Egyptian city of Hurgada from a mixture of four separate hybrid renewable sources: solar photovoltaics (SPV), wind turbines, diesel engines, and storage batteries. HOMER software was used to conduct the simulation results, optimization, and modelling procedures. The combination of SPV-wind-diesel-battery source was found to have less cost of energy of 0.275\$/kWh compared with the cost of 0.36\$/kWh for the SPV-diesel combination.

Hydrogen is a potential energy carrier for renewable energy (Martin et al., 2020) as it has a clean emission when consumed. To implement hydrogen energy system in large-scale, a comprehensive hydrogen supply network should be built to supply the required hydrogen with optimal infrastructure arrangement. Mah et al. (2022) investigated the viability of an integrated hydrogen-electricity supply chain for the region of Johor, Malaysia through a spatial optimization framework that integrated geographical information with mathematical modeling for the design and optimization of a photovoltaic-based hydrogen-electricity supply chain. The proposed framework allowed the concurrent targeting of vehicle fuel and electricity demands as well as the identification of suitable locations for supply chain infrastructures. The case study results show that the minimum cost of hydrogen-electricity supply chain is about 14.9 billion USD/y assuming two days of autonomy, and that the cost of battery constitutes 43% of the total supply chain cost. When the days of autonomy is eight and above, hydrogen storage is preferred and electricity is regenerated from hydrogen using fuel cell.

There have been several recent studies of possibility of 100% RES at a regional level. Khoie et al. (2019) investigated energy mix strategies for regions of northern half of United States to go 100% renewable (solar PV, onshore wind, hydro, biomass and geothermal) and concluded that the West Coast, Mountain and Middle West regions could do so by around 2040 while Lake states, Mid-Atlantic, South Atlantic and New England states would not be able to reach this target even by 2050. Dong et al. (2020) in their paper have shown that interconnecting intermittent renewable energy (IRE) and nuclear to provide clean energy reliably and continuously on a wide scale is appealing due to their complementarity. The IRE can be integrated more easily by actively modifying the electric power output of nuclear cogeneration plants (NCPs), which results in regular redistribution of main steam to the turbine and cogeneration process.

National power, heating, cooling, and transportation systems must all achieve zero emissions in the future. To ensure the reliability of energy supply in 100 percent renewable energy systems, a large number of backup power plants as well as large-scale energy storage capacity are needed. Electricity can be partially converted into hydrogen, which can then be transported through pipelines, stored in large amounts in underground salt caverns to avoid seasonal effects, and used as electricity storage or a renewable transportation fuel. Oldenbroek et al. (2021) show how hydrogen-fueled fuel cell electric vehicles parked and connected to the grid in Denmark, Germany, the United Kingdom, France, and Spain could balance 100 percent renewable energy, heating, cooling, and transportation systems at the national level. Kumar and Jayanti (2021) have examined the possibility of the southern states of India going 100% renewable through distributed photovoltaic power generation (DPPG) coupled with existing wind, hydro and nuclear power sources. Cecen et al. (2022) present a SWOT (strength, weakness, opportunity and threat) analysis of the development of the DPPG sector in Turkey.

Load management under dominant renewables contribution to power generation has received quite a lot of attention in recent years. Ogunjuyigbe et al. (2015) offer a load allocation management system based on a set of rules implemented by the Modified Mild Intrusive Genetic Algorithm (MMIGA), which will fit the house owner's economical solar system inverter. In both abundant and insufficient energy supply, the algorithm optimized load allocation in real time. MMIGA is then used to intelligently generate a series of bits, which are subsequently implemented by the hardware according to a set of rules. A daily load discrimination profile is first developed, followed by the construction of a priority matrix for the relevant time of day. The suggested algorithm achieves the goals of being cost-effective, intelligent, and simple to use, and it can be applied to a variety of load profiles.

Electrical energy storage is often suggested as a key to the mismatch between supply and demand tendencies of erratic renewable electricity sources. However, the efficacy and utility of storage can vary depending on the situation. At a meso-level, residential sector background, the study by Laugs et al. (2020) offers a theoretical viewpoint on the merits of electrical energy storage combined with devolved supply systems consisting of solar PV and wind power. They used a balancing model based on Dutch weather data to couple demand and supply trends and determine the resulting loads under various scenarios. The results of the model show noteworthy differences in storage efficiency between solar PV and wind power, as well as robust diminishing-returns effects. Small storage capacities can help reduce

excesses in over-dimensioned supply systems as well as scarcities in under-dimensioned supply systems. However, total imbalance removal demands large storage capacities.

Liu et al. (2020) have projected a power system electricity frequency control technique for a 100% renewable energy inaccessible power grid using model predictive control (MPC). Large capacity PV generation and storage batteries were presented based on an original 100 percent renewable energy power system as the price of PV panels and storage batteries fell considerably in these years. To match consumption and generation, MPCs were designed for each model (photovoltaic generation, wind turbine, storage battery, fuel cell and seawater electrolyser). In addition, demand response (real-time pricing) was used in this structure to lessen the load frequency by regulating the controllable loads.

Power systems that rely heavily on sporadic renewable electricity production, such as wind and solar, require a high level of suppleness in both power generation and demand. Heat pumps and combined heat and power units in district heating systems, as well as thermal storages, have all been scrutinized in the past for their ability to recover the energy system's adaptability. These technologies must be handled in a non-standard manner with swapped merit-order when used for power balancing. Monie et al. (2021) propose that a residential area could form a locally operated entity, such as a virtual power plant, that offers power-balancing services to a national power system. The theory is tested in a case study in Sweden, where the local agency consists of a combined heat and power plant, heat pumps, a local heat distribution system, and thermal storage. A simulation of the energy balances in the system was run with storage size optimization. The heat pumps devour all of the system's power excesses, according to the results. The mutual heat and power unit covers 43% of the annual load and 21% of the electricity peak load. Inter-seasonal thermal storage, it is concluded, is important for the system's versatility. Huge energy surpluses, when converted to heat and stored, restrict the virtual power plant's ability to use the combined heat and power unit for power balancing later. Despite this, a local virtual power plant may provide enhanced flexibility to the power grid by providing power-balancing services.

Future grid systems can be more energy efficient and stable if proper energy conservation strategies and renewable energy resources are implemented. Sarkar et al. (2020) have suggested a microgrid architecture and demand side management (DSM) technique for home energy management. Household loads were moved on the basis of price-based tariffs such as flexible and time-of-use tariffs to reduce peak load, peak to average, and energy costs. The binary particle swarm optimization algorithm was used to simulate the situation. According to simulations, DSM implementation resulted in a substantial reduction in peak loads and a trade-off between renewable resources and peak loads. By paying less for power and selling the surplus electricity to the grid, renewable energy incorporation with DSM could be a promising solution for significantly lowering overall electricity costs for households. Golla et al. (2021) presented a new control technique for a solar photovoltaic (PV) integrated universal active power filter (PV-UAPF). PV integration at the DC link will also lower demand on the supply system, easing the load on the utility grid. As a result, the suggested system combines the advantages of clean energy generation with improved power quality. The system's performance is further tested in the hardware configuration under various disturbances such as voltage sag/swell, load distortion, and PV power variation.

Boddapati & Nandikatti (2020) examined the impacts of the Government of India's 9-minute pan-India voluntary lights-off policy, which was planned and implemented in April 2020, on the National Grid, as well as the efforts taken to ensure grid stability during the event. In the nation's fight against the epidemic, the policy was a symbolic expression of public support with frontline healthcare and emergency workers. The technique used by the Indian power industry to control the grid during the nine-minute incident was discussed in this article. Variations in grid characteristics such as frequency, voltage, and load are assessed at all dispatch centres before, during, and after the nine-minute period, and the generation plan followed was displayed, along with real-time findings. This case study presents an overview of power system management, which includes strategic generator scheduling across the country to address abrupt and massive demand decreases on the power system.

Thus it can be said that integration of renewable energy for local/ regional power supply has received significant attention in recent years from different perspectives. While the potential for 100% renewable power generation has been studied at a regional scale from an overall energy balance point of view, studies on utility-scale balancing of consumer demand with hybrid power sources have not been reported. Specifically, the issue of energy storage requirements and possible technological solutions has not been addressed in a comprehensive way. Against this background, we propose a heuristic model that integrates (geographically) distributed and diverse power sources with geographically spread-out power consumption centres and diverse electrical energy storage systems through transmission and storage loss models. For a regional electricity grid, the model computes, over a given day, the minute-by-minute power demand from and power generation in each district, extracts matching power from a hierarchy of power sources so as to minimize transmission and storage losses, and stores excess power in a variety of power storage options. The model can thus generate useful insight into planning for regional establishment of power generation/ storage systems to meet CO<sub>2</sub>-neutral electricity demand at power grid level.

## **2. Model Description**

### **2.1 Overview of the model**

The model is focused on balancing power generation and power demand over a day in such a way that the minute-by-minute power demand of a district (which is an administrative region within a state; the latter is a political entity that has an elected government) from available power sources and energy storage systems is completely met. The model considers two types of utility-scale power sources: those, such as solar PV, wind and nuclear, whose power output needs to be used instantly, and those energy storage devices, such as hydro, pumped hydro, batteries, fuel cells, whose power output can be drawn at will (provided there is stored energy). The utility-scale energy storage systems can be further classified into two types, namely, the conventional storage systems such as hydro-electric plants and pumped hydro-electric plants, and the new-age and yet-to-be-built utility-scale electrochemical/chemical energy storage systems such as batteries, reversible fuel cells (essentially, integrated units that can work in

electrolyser and fuel cell mode) and hydrogen-based energy storage and retrieval systems. All these sources are localized to the district level in terms of geographical spread. The district-wise electrical energy demand for a particular day of interest is estimated and is then broken up into minute-by-minute demand using a power demand profile. In the first stage of power allocation, starting with time = 0 (arbitrarily set to midnight), minute-by-minute power from the instant power sources, namely, solar PV, wind and nuclear is allocated to each power consuming centre using the Inter-District Energy Exchange (IDEE) algorithm described in Kumar & Jayanti (2021) which is a banded energy exchange algorithm involving sequential inter-district energy exchanges according to a specific banded layout of transmission loss that depends on the inter-district distance. When this is done for all the districts for all the 1440 minutes of the day, each district has a power surplus or deficit for each minute. In the second stage, power drawn from conventional and already existing energy sources (hydro and a fully-charged pumped-hydroelectric plants) is allocated sequentially in time only to the districts having deficit power, using the IDEE algorithm. This will reduce the deficit in some districts but the surplus districts remain unaffected. This information is used to determine the location and capacity of the battery/chemical energy storage units. In the third stage of energy allocation, the surplus energy in the surplus districts is transmitted using the IDEE algorithm to the deficit districts and replenishable energy sources (PHS which stands for Pumped Hydro Scheme, and electrochemical/ chemical energy storage systems), taking account of transmission loss and storage loss for each energy exchange. If sufficient generation and storage are allocated, this will result in nullifying the deficit in all districts in each of the 1440 minute-size time slices while leaving little surplus energy.

## 2.2 Model Assumptions and Limitations

- The model is energy-based rather than power-based, i.e., it deals with energy generated or demanded over a minute and does not consider, for example, the variation of efficiency with power. The power generation efficiency is assumed to be constant.
- The spatial resolution of the model is a district, which is a political administrative unit (which is headed by a District Collector). The geographical size, population and energy demand of a district are not constant and can vary widely. The case of south India considered in the present work has a total of 99 districts.
- The daily and over-the-day energy demand in each district are not based directly on data but have been estimated as explained later. The variation does not account for random fluctuations within the day but has district-specific variation induced by sun's location over the day in the case of solar PV. Wind power is assumed to be constant throughout the day for the want of better information while nuclear power plants are assumed to be operated at a constant power output throughout the day.
- The model does not account for the start-up or shut-down or ramp rate dynamics of the power sources. However, the stored-power sources do include batteries, hydro and pumped-hydro plants that have fairly quick response.

On the whole, the model is an arithmetic model that does energy audit of power sources and sinks every minute. It incorporates the transmission loss minimizing Inter-District Energy Exchange (IDEE) algorithm

for power allocation every minute which only requires sequential steps of arithmetic calculations. Details of the model are described below in the context of its application to the regional power grid comprising the five major states of south India, namely, Andhra Pradesh, Telangana, Karnataka, Kerala and Tamil Nadu. Together, these five states account for a population of 285 million and have an annual electricity consumption of about 350 TWh.

## 2.3 Power Consumption Profile

The electrical energy demand in each district is based on our previous study (Kumar and Jayanti, 2021) wherein annual electricity consumption within a collection of districts within each state was reconstructed from annual reports of the State Electricity Boards and other governmental sources. This was then distributed among the participating districts of the region based on the population in each district. The district-wise annual electricity consumption thus obtained in the previous work is divided by 365 to obtain the daily electricity demand for the district. To obtain the minute-by-minute variation, representative state-wise electricity demand profiles (see Fig. 1) from an NREL report (Palchak et al., 2017) have been used. It may be noted that the variation of consumption pattern for the individual districts of any given state follows the same trend as the parent state for any given day. One can see that these variations, typical of mid-July, indicate a strong electrical power demand throughout the day with small peaks in the early morning and early evening. These profiles have been used to determine the minute-by-minute district-wise electrical energy demand. The idea is to meet this demand from non-CO<sub>2</sub> emitting power sources over the entire day.

## 2.4 Power Sources

The following power sources are considered in the present study:

- Distributed solar PV using barren, rocky type of waste land as per availability in each district. The estimated power generation capacity in each district is outlined in a previous work by the present authors (Kumar and Jayanti, 2021). The minute-by-minute power generation is based on the time of the day and the geographical location of the district while total daily output ( $E_s$ ) is based on the local global horizontal irradiance ( $G$ ), cell efficiency ( $\eta$ ), capacity utilization factor ( $C$ ) and area of PV panels ( $A$ ):

$$E_s = G \eta C A (1)$$

Estimates for these have been presented in our earlier work (Kumar and Jayanti, 2021) based on available data. This information is used in the present work to determine the minute-by-minute variation of solar PV output in the following way. Based on the coordinates of each district, the sunrise and the sunset times on July 15th (which is taken as representative day for the month of July) have been obtained. The difference between the two constitutes the sunshine hours,  $T$ . It is assumed that the temporal variation of power output ( $h$ ) from a PV panel can be represented by a parabola (Fig. 2):



$$h = H - 4 (H/T^2) (\tau - T/2)^2 \quad (2)$$

where  $H$  is the peak power and  $\tau$  is the time elapsed from sunrise. Integrating the above expression over  $T$  and equating it to  $E_s$ , the total energy output per day, gives

$$H = 3E_s/(2T) \quad (3)$$

The units of the aforementioned variables should be consistent; the units used in the present study are  $E_s$  (GWh),  $G$  (kWh/(m<sup>2</sup>.day)),  $A$  (km<sup>2</sup>),  $h$  (GW),  $H$  (GW),  $T$  (h). The numerical values of some variables may vary with day of the year and the geographical location; the values for the 13 states of Andhra Pradesh are listed in Table 1 where  $A$  is the (barren rocky) waste land area available for PV-based power generation in each district.

Table 1  
Numerical values for the variables in the power generation model used in this work for the 13 districts of Andhra Pradesh

District	G (kWh/m <sup>2</sup> /day)	$\eta$	C	A (km <sup>2</sup> )	$E_s$ (GWh)	H (GW)	T(h)
Anantapur	5.45	0.15	0.18	539.42	79.38	9.22	12.92
Chittoor	5.43	0.15	0.18	272.68	39.98	4.67	12.83
East Godavari	5.42	0.15	0.18	0.56	0.08	0.01	13.10
Guntur	5.89	0.15	0.18	486.79	77.41	8.93	13.00
Krishna	5.87	0.15	0.18	3.60	0.57	0.07	13.00
Kurnool	5.35	0.15	0.18	735.43	106.23	12.29	12.97
Nellore	5.42	0.15	0.18	8.95	1.31	0.15	12.90
Prakasam	5.91	0.15	0.18	116.57	18.60	2.15	12.97
Srikakulam	5.92	0.15	0.18	8.94	1.43	0.16	13.13
Visakhapatnam	5.85	0.15	0.18	11.91	1.88	0.22	13.08
Vizianagaram	5.72	0.15	0.18	23.02	3.56	0.41	13.13
West Godavari	5.51	0.15	0.18	0.10	0.01	0.00	13.05
Kadapa	5.56	0.15	0.18	288.61	43.33	5.04	12.90

From estimated  $E_s$  and from known sunrise and sunset times for each district, the solar energy output can be computed using Eq. (2) at any time during the sunshine hours. The output is assumed to be zero before sunrise and after sunset. Eq. (2) is integrated over each minute to find the minute-by-minute solar

energy output in each district. Since the coordinates of each district are used to determine the sunrise and sunset, the model accounts for the small shift in the solar energy output among different districts.

- Nuclear power is based on existing installations. The amount of power generated is based on the data of annual nuclear power plant output (CEA, 2020). It is assumed that the nuclear power plants operate at constant power throughout the day. The annual nuclear power plant output divided by  $(365 \times 1440)$  thus gives the per-minute generation of electrical energy from that unit. The nuclear power plant is localized to the district in which the power plant is located. A transmission loss model is used to allocate this power to other districts.
- Wind power too is based on data of annual wind power output in the year 2020. State-wise information is available from government sources together with monthly variation of wind power generation in each state. The wind energy generated per day is estimated by the dividing by 31 the total wind energy generated in each state in the month of July. For want of detailed information on wind power variation over the day, the daily wind energy generation is divided by 1440 to obtain the wind energy generation per minute in the state. This is further divided by the number of districts in the state to obtain the district-wise minute-by-minute wind energy generation.
- In addition to power from solar PV, wind and nuclear power plants, electrical power from storage systems is also considered. Of these, hydro power and pumped-hydro power have been considered based on existing capacity in the five states. Two new storage systems (which are further discussed in the next section), namely, electrochemical battery and reversible solid oxide fuel cells (ReSOC), are not yet in place anywhere. The size, location and storage capacity of these units are determined as part of the application of the present model, as explained later. All energy storage systems have been localized to the district level, i.e., their power output and storage capacity have been allocated to the district in which they are located. This will be helpful in making accurate estimate of transmission losses.

## 2.5 Energy Storage Systems

In an energy mix scenario in which solar power is the main contributor, energy storage systems are necessary to store the excess renewable energy produced during day-time and release it when needed in off-sunshine hours. Two types of energy storage units are considered in the present study for utility-scale application:

- Conventional storage units comprising of large hydro-electricity (hydel) plants and pumped hydropower storage plants. Hydel plants are present in all the five states and form an important source of power. Given the opposition to more large-scale hydel plants, it is expected that hydro-electricity potential through construction of large dams is already exhausted in India. Information from websites of state electricity boards and ministry sources, hydro-electricity generated per day averaged over the month of July has been estimated from each plant and has been resolved to district level. Utility-scale pumped hydro storage (PHS) systems are very few. There are only two such PHS units that are operational (one in Tamil Nadu and another one in Andhra Pradesh) and one unit

is under construction in the state of Telangana. The location and storage capacity of each of these is listed in Table 2. PHS is an attractive storage scheme for day-night balancing with a round-trip energy efficiency of the order of 70 to 80% (Buckley, 2019) and is useful in time-shifting electricity to peak demand periods, allowing power to be stored when it is cheapest and then used when prices are greatest. While more PHS units may be built in future, in the present study, we consider only the above three, which have a cumulative power capacity of nearly 2000 MW.

- Available conventional energy storage options fall well short of the need. While a variety of energy storage schemes are available or are being developed, those suitable for grid-scale applications are few in number. In the present study, we consider two “new-age” energy storage technologies: electrochemical batteries (lithium-ion batteries, sodium-sulphur batteries, flow batteries, etc.) which are being built in capacities in excess of 100 MW, and integrated electrolyser-fuel cell units, which electrochemically convert excess electricity to hydrogen and use it in one of several ways to produce electricity at a later time. Recent studies (Jensen et al., 2015; Wang et al., 2020) show that a power-to-x-to-power system based on reversible solid oxide cell, referred to ReSOC henceforth, can have high round-trip energy efficiencies in the range of 40 to 70%. In these systems, a single solid oxide cell can work in both electrolyser mode (producing chemical fuel) and fuel cell mode (producing electricity using the previously-produced chemical fuel); heat integration between the two modes of operation and optimal choice of the fuel composition are essential to achieve high round-trip efficiency. Some estimates (Jensen et al., 2015) show that such systems can be cost-competitive too when implemented for large-scale energy storage. In view of this, in the present study, we consider rechargeable, utility-scale batteries and reversible solid oxide cell units as additional electrical energy storage systems. Of these, batteries can instantly switch between power and storage modes while ReSOC systems are likely to take several minutes to switch over from one mode to the other. We assume that these units, typically, of hundreds of megawatt power capacity will be used in optimal locations to balance source and demand. It may be noted that, as per internet reports, batteries (both lithium-based and vanadium redox flow batteries) of up to 2 GWh storage capacity are being installed in California and elsewhere. The power rating of ReSOC is based on the paper of Jensen et al. (2015) who considered a system of 250 MW power rating. The energy rating of an ReSOC system is independent of its power rating and depends on the storage tank capacity. Jensen et al. (2015) performed calculations for a storage capacity of 500 GWh.

Some power will be lost in converting from electrical power and some more will be lost when the chemical energy is reconverted back to electricity. Some energy loss may also occur during storage. The round-trip energy efficiency, i.e., the ratio of energy retrieved after storage to energy sent for storing, depends on a number of factors, including the rate at which energy is being stored (i.e., charging power) and the rate at which it is being discharged. Despite this, in the present study, we assume the round-trip efficiencies to be constant as given below:

Pumped Hydro Storage: 72%

ReSOC: 60%

Battery: 80%

PHS has a round trip efficiency of 70–80%, depending upon the distance and gradient separating upper and lower reservoirs (Buckley and Shah, 2019). Thus an efficiency value of 85% for charging and 85% for discharging giving a round-trip efficiency of 72% is reasonable. Similarly, the round-trip efficiency of Li-ion batteries as obtained from literature (Nikolaidis and Poullikkas, 2018) can approach 100%. At a system level for a large installation, where a number of auxiliary systems need to be used, and over a lifetime, a battery efficiency of 80% is reasonable. The assumed value of efficiency of ReSOC is based on Jensen et al. (2015).

## 2.6 Transmission Loss Minimization

In a decentralized power generation scenario with a major share of power coming from solar PV, one can anticipate energy exchanges among power producing stations, power consuming stations and power storage systems. A significant amount of power produced during daytime may need to be sent for storage only to be re-generated after several hours for distribution to needy power consumers. In the present study, we use the Inter-District Energy Exchange (IDEE) algorithm developed previously (Kumar and Jayanti, 2021) to distribute energy available with several “surplus” districts to several other energy “deficit” districts. Since the power demand as well as power availability may vary dynamically, at any given instant, there may be several of these in each category and the choice which generating station distributes to which receiving station is not unique or obvious. The algorithm ensures that this energy exchange is done with minimal transmission loss.

## 2.7 Flow chart of the model

The model calculation proceeds as follows. To begin with, the entire geographical region is divided into local administrative regions which become the centres for power generation or consumption. In the present case, these are taken to be the districts, each of which is administered by a district collector. The waste land of barren rocky type available in each district (for solar PV generation), the prevalence of other power sources (wind, nuclear), the daily energy consumption, the existence of hydropower plant and pumped hydro storage (PHS) potential, and the inter-district transmission loss coefficient (expressed in discrete “bands” of 0.05, 0.08, 0.12 and 0.15) are all part of the input. In Step I of the model (see Fig. 3), the energy consumption per day in each district is discretized into 1440 slices, each representing the energy consumption per minute in that district. In Step II of the model, the available power from solar PV, wind and nuclear are computed in each district for every minute. In Step III, the IDEE algorithm is used to distribute energy available in each district every minute to all the needy districts *at that* minute, i.e., without consideration of storage. At the end of Step III, we have, for every minute and for each district, the amount of surplus or deficit energy. In Step IV, hydro energy available in each district is distributed once again using the IDEE algorithm so as to minimize requirement for energy storage.

At the end of Step IV, the amount of surplus/ deficit energy in each district at each time instant is known. Note that at each minute, there can only be either surplus districts or deficit districts. Meeting the deficit through surplus needs to follow the logic of subsequence, i.e., store first and reuse later. The location of

storage stations and their capacity also needs to be known. These are done in separate steps as explained below. In Step V of the present model, the location of each storage station (Battery or ReSOC or both) is determined as follows:

- \* one battery storage station of 400 MW power capacity and 1.6 GWh is placed in all the surplus districts and the top ten energy consumption districts (so that they can also serve to smoothen power fluctuations to some extent).

- \* in all surplus districts, an ReSOC system of power rating in multiples of 250 MW has is placed such that the remaining surplus energy can be charged in about 10 hours. This is based on the observation that solar energy surplus persists for about 10 hours in the districts with large solar farms. A further consideration in the sizing of the battery and ReSOC systems is that battery storage, though advantageous from higher system efficiency and instant switch-over point of view, is expected to be more expensive than ReSOC when scaled to utility-scale storage systems.

In Step VI, choosing an appropriate starting point in time (e.g. 5.30 pm) and with initial amount of stored energy (e.g., 95% of capacity charged at 5.30 pm), the minute-by-minute deficit is eliminated sequentially. For example, at 5.31 pm, the amount of deficit available in each district is satisfied from these storage units using the IDEE algorithm. If, at a later point of time, surplus energy is available (for example, at 10.01 am when the sun is up), then that surplus is used to charge storage units at that time, once again using the IDEE algorithm. It may be noted that the round-trip energy efficiency of the storage system is discounted at this charging step itself. For example, if 1 GWh is to be stored in an ReSOC unit having efficiency of 0.60, then its energy content is enhanced only by 0.6 GWh and 1 GWh is subtracted from the energy content of the supplying unit. Finally, if all the energy reservoirs are full, then the surplus energy remains with the district at that time instant. This process of deficit reduction is carried out for every district time step by time step for all the 1440 minutes taken in a sequence.

At the end of Step VI, there are three possibilities which have a bearing on the sizing of the energy storage units. If all the deficit at every minute of the day is nullified and some surplus energy is remaining in some time intervals and if the storage capacity of the units has reached the levels assumed at the beginning, then one may conclude that the storage capacity of each unit has been chosen well and the land allocated for solar PV generation can be reduced, if it is found to be excessively high. However, if the storage capacity at the end time cycle is less than what has been assumed, and if surplus energy is available, then the capacity of the storage units in those surplus districts should be increased and the model should be re-run until all the surplus is rendered zero. If the energy levels of the storage units are not restored to the levels at the beginning even after this, then one can conclude that 100% decarbonization is not sustainable unless new CO<sub>2</sub>-neutral sources can be found. The fraction of RE in the energy mix is a sensitive parameter in the progression towards zero-carbon society. If the fraction is too small and is not compensated by CO<sub>2</sub> reduction in other sectors, then perhaps more should be done, for example, by designing/using better PV cells or PV systems with sun-tracking systems, or exploiting less economical RE sources, for example, off-shore wind turbines, small hydropower plants that are

seasonal, etc. For this reason, an estimate of % of electricity consumption met by RE sources needs to be evaluated and is done as part of Step VII tasks.

### 3. Application Of Model To Regional Electricity Grid Of South India

The five major states of South India, namely, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh and Telangana, account for about one-fifth of the total electricity consumption of India. The daily consumption for the 23rd of July, 2020, as reported by CEA (2020) is 162.12, 66.84, 296.77, 154.35 and 173.04 GWh, respectively, for these five states. In the present study, this state-wide consumption is partitioned into district-wise consumption as per the procedure reported in our earlier work (Kumar and Jayanti, 2021) where data from CEA (2020) for the 23rd of July, 2020 was first used to construct a regional power consumption profile within the state, and the regional consumption was then apportioned among the districts lying within the region on a per-capita basis. In the present study, this district-wise daily consumption is broken up into minute-by-minute power requirement that needs to be met by the various non-GHG power sources described in Sections 2.4 and 2.5. All the data required for the execution of Steps I and II of the model are summarized in Fig. 4. Figure 4a shows the normalized state-wise consumption of electricity over a day in the five states. Three of these profiles (for Karnataka, Andhra Pradesh and Tamil Nadu) were available from NREL Report by Palchak et al. (2017), while the profiles for Kerala and Telangana have been obtained as the average of the profiles of two neighboring states. By adding together in proportion of the total daily consumption, one can observe that 64% of the total daily consumption occurs during sunshine hours and the remaining occurs in the period after sunset and before sunrise. Figure 4b shows the electricity consumption in each district on the chosen day. Figure 4c shows the normalized district-wise solar PV generation on 90% of the barren, rocky waste land available in each district. Figure 4d shows the normalized district-wise wind power generation. Figure 4e shows the daily availability of nuclear, hydro and pumped hydel storage, each source being shown on its own relative scale. One can see that there is a significant regional variation in both demand for electricity and the generation capacity. Thus, inter-district exchange of energy is necessary for regional balancing of demand and supply.

Using a banded structure for inter-district transmission loss, in which a transmission loss factor of 0.05, 0.08, 0.12 and 0.15 has been used for adjacent, neighboring, near and far districts, respectively (Kumar & Jayanti, 2021), the solar, wind and nuclear energy available every minute has been distributed over all the districts to meet the demand in that minute, as per the Step III process. The starting point for this step is not important as no energy storage unit is used; once the calculation is done for all the 1440 minutes of the day, we have the minute-by-minute variation of deficit or surplus for each district. Figure 5a shows five profiles, one each for one selected district from each state, to show the variability from time to time as well as from region to region. This needs to be met from available energy sources.

Of the energy sources included in the present study, power from large hydro-electric (hydel) power plants is considered to be non-replenishable, i.e. it cannot be re-charged during the day. Each hydel power station is thus characterized by a quantum of energy (subject to a maximum power rating of hydroturbines)

available for disbursement during the day. In contrast, pumped hydropower storage (PHS) is considered to be replenishable (like batteries and reversible solid oxide cell storage units) during the day if there is a need or opportunity. The energy content in these storage units can both decrease and increase depending on whether they are discharged or recharged. Since these are energy reservoirs, they need an initial condition, i.e., the amount of stored energy at a given reference time, needs to be specified. Noting that most of the surplus energy occurs during the mid-day in a renewable mix dominated by solar PV, it is assumed that the replenishable energy reservoirs have an energy level of 95% of their capacity at 5.48 pm ( $T = 1068$  min), which is close to the sunset time, and Step IV and subsequent calculations are started from  $T = 1069$  and are taken through the night, the following morning and up to 5.48 pm on the following afternoon. Thus hydel power utilization is done in Step IV to clear the deficit starting from  $T = 1069$  min. At each minute, the power output from each hydel station is distributed among districts using the IDEE algorithm to minimize transmission losses. One may be able to argue that, strictly speaking, the starting point does not matter as the energy auditing is being done over a 24-hour period. The stored energy can, notionally, go negative and be replenished later by available excess power. As long as the reservoir capacity is brought back to the assumed value at the end of the 24-hour period, it does not matter what the starting time is and what initial capacities are in Step VI. However, one can avoid stored energy going negative by choosing an appropriate starting point.

In Step V of the model, the location and capacity of battery storage plants and ReSOC storage plants have been fixed based on the availability of large energy surplus with the further restriction that the individual battery storage capacity is 1.6 GWh with a power rating of 0.4 GW and the rest is that of ReSOC, given that the former is likely to be expensive on a per kWh basis (Jensen et al., 2015). The results of implementation of this step are shown in Fig. 5b which indicates the districts in which the three replenishable energy sources are present; their capacity and power rating is listed in Table 2. These are then used in Step VI to reduce the minute-by-minute deficit reduction starting from  $T = 1069$  min. The results of this exercise are discussed below.

Figure 6 summarizes the overall energy flow among the various components of the model. The primary power produced by solar, wind, nuclear and hydel plants is shared among the five states, which receive power directly from the primary power producers as well as from the three replenishable energy storage units. The diagram also identifies transmission loss and storage loss (accounting for loss during charging and loss during power generation later) as additional sink terms for the power generated. About 70% of total electrical energy generated comes from solar PV while wind, nuclear and hydel plants contribute 15.5, 5 and 9.5%, respectively. About 53.4% of the power produced by solar PV is used to meet demand of states directly while the rest goes for storage (to ReSOC, PHS and Battery) and transmission loss. In the case of wind and nuclear, which are assumed to produce constant power throughout the day (including night), 59.3% and 66.8%, respectively, is used to meet states' demands directly while the rest is used up for storage and loss. Hydro power, which is treated as a quantum of energy available per day, has been used entirely to meet demand after sunset and involves no storage loss. How much of each resource is used for storage depends on the geographic as well as temporal variation of power demand and power generation, and is effectively determined by the IDEE algorithm at each instant.

Table 2  
Location and rating of replenishable energy sources in south India.

S.No.	District	Energy rating PHS (GWh)	Power rating PHS (GW)	Energy rating Battery (GWh)	Power rating Battery (GW)	Energy rating ReSOC (GWh)	Power rating ReSOC (GW)
1	Ballari			1.6	0.4		
2	Gulbarga			1.6	0.4		
3	Raichur			1.6	0.4	6.81	0.75
4	Uttara Kannada			1.6	0.4	1.71	0.25
5	Mandya			1.6	0.4		
6	Dakshina Kannada			1.6	0.4	10.28	1.25
7	Gadag			1.6	0.4	3.63	0.5
8	Kodagu			1.6	0.4	3.95	0.5
9	Chamarajanagar			1.6	0.4	4.46	0.5
10	Yadgir			1.6	0.4		
11	Bidar			1.6	0.4		
12	Haveri			1.6	0.4	0.69	0.25
13	Davanagere			1.6	0.4	1.09	0.25
14	Dharwad			1.6	0.4		
15	Shivamogga			1.6	0.4	6.39	0.75
16	Belgaum			1.6	0.4	6.87	0.75
17	Ramanagara			1.6	0.4		
18	Bengaluru Urban			1.6	0.4		
19	Chennai			1.6	0.4		
20	Tirunelveli			1.6	0.4	0.51	0.25
21	Coimbatore	4.71	0.4				
22	Anantapur			1.6	0.4	35.01	3.5
23	Chittoor			1.6	0.4		
24	Guntur			1.6	0.4	31.78	3.25



S.No.	District	Energy rating PHS (GWh)	Power rating PHS (GW)	Energy rating Battery (GWh)	Power rating Battery (GW)	Energy rating ReSOC (GWh)	Power rating ReSOC (GW)
25	YSR Kadapa district			1.6	0.4	16.77	1.75
26	Kurnool	10.59	0.9	1.6	0.4	42.35	4.25
27	Prakasam			1.6	0.4	5.59	0.75
28	Nizamabad			1.6	0.4		
29	Medak			1.6	0.4		
30	Ranga Reddy			1.6	0.4		
31	Hyderabad			1.6	0.4		
32	Mahabubnagar			1.6	0.4	3.58	0.5
33	Nalgonda	8.29	0.705	1.6	0.4		
34	Warangal			1.6	0.4		
35	Karimnagar			1.6	0.4		
36	Palakkad			1.6	0.4		
37	Idukki			1.6	0.4		

Figure 7 shows the energy flows from the four primary power providers in more detail. A total of 1084.7 GWh is produced of which 771 GWh is produced by solar PV panels located on 90% of barren, rocky waste land available in each of the 99 districts. A capacity utilization factor (CUF) of 22% has been assumed for these PV plants. Wind, nuclear and hydropower contribute a further 162.5, 51.9 and 99.4 GWh, respectively. These are based on actuals for the year April 2019 to March 2020. One may note that on-shore wind potential in south India is rather limited as is large hydro, and much of the available potential has already been tapped. Nuclear energy production has been increasing steadily over the years with the addition of new reactors but the pace of increase is limited by a number of factors. Due to the large dependence on solar power, a significant portion of the PV output, amounting to 327 GWh, is directed to energy storage units for night time power generation. Taking into account the contribution from wind and nuclear, the total energy storage requirement is found to be 406 GWh. Pumped hydro scheme, based on actuals, accounts for only 33.6 GWh implying that 372.3 GWh of energy storage is required through battery and reversible solid oxide cells.

Figure 8 shows details of cumulative electrical energy delivered over the day to the five major states of South India from various power sources including the three replenishable energy storage devices. Karnataka and Tamil Nadu have relatively high day time consumption of power compared to the other three states. Model results that, despite this, solar power accounts for only 44.1% daily electrical energy

requirement for Tamil Nadu compared to 51.9% for Karnataka. This can be attributed to the preferential use of “local” power sources through the IDEE algorithm. Accordingly, Tamil Nadu draws a higher amount, as well as proportion, of its power requirement from wind and nuclear. By the same token, it can be seen that Telangana state, which has very little wind power and nearly no nuclear power plants, draws only about 1% of its power requirement from these two sources. Reflecting the higher relative fraction of daily energy requirement during off-sunshine hours, Andhra Pradesh, Telangana and Kerala, draw a relatively high fraction, amounting to 25.7, 32.8 and 30.0%, respectively, from yet-to-be-installed electrochemical energy storage systems, namely, Battery and ReSOC units. This fractional dependence for Karnataka is only 16.9%. Thus, the individual states have different degrees of dependence on energy storage in their quest for carbon-neutral electricity generation.

An important factor associated with energy storage is the storage loss, i.e. energy losses that need to be incurred first during charging and later during discharging. The round-trip energy efficiency varies on a number of factors. In the present study, a ball-park figure of 72%, 80% and 60% have been assumed for PHS, battery and ReSOC-based energy storage systems. However, the effective storage loss can be significantly less because a large fraction of generated power is used instantly, i.e., without storage. The present calculations show that the overall energy flow is such that out of the 1084.7 GWh energy generated, 853 GWh is supplied to the 99 districts with 40.3 GWh as buffer surplus. There is thus a loss of 22.1% in transmission, distribution and storage. Because of local consumption of electricity, the transmission and distribution losses amount to about 8.45% while the rest is attributed to storage losses (including charging and discharging) in PHS, Battery and ReSOC storage stations.

Finally, the predicted deployment over the day of the energy sources is illustrated in Fig. 9a wherein the deliverable energy level of each source is plotted as a function of time. It can be seen that PHS is the smallest with a total energy capacity of 23.6 GWh, followed by battery, hydro and ReSOC with deliverable, i.e., after accounting for storage loss, energy capacity of 57.6, 99.4 and 181.5 GWh. The discharge calculation in Step VI starts at  $T = 1069$  min (5.49 pm) at which point all storage units are assumed to be 100% full. One can see that the overall power demand is such that it can be satisfied by operating hydropower first from 5.49 pm, then PHS, then ReSOC and finally the battery. By the time all these are exhausted at 428 min (7.08 am), power from other sources (wind, nuclear and PV) is sufficient to meet the demand; excess power is used to charge the energy storage units. Figure 9b shows the minute-by-minute net power deficit or surplus over the day for all the five states put together. It may be noted as per the IDEE algorithm, at any minute there can be either deficit or surplus; the two cannot be non-zero simultaneously. Further, surplus power here indicates the additional power that cannot be charged to the energy storage units either because the storage units are full or because power available is greater than the maximum power at which they can be charged. It can be seen from Fig. 9b that there is no deficit at any point of time and that there is a small surplus (amounting to less than 5% of the total energy demand) during part of the sunshine hours. If this surplus is not converted economically to easily storable fuels (e.g. methanol), then solar PV generation should be curtailed during the surplus period. The fact that the surplus is small compared to the total daily energy use indicates that the storage capacities

are sized properly. The surplus can also serve as a small cushion to counter the day-to-day variability of renewable power sources.

Comparing the present results with some of the studies discussed in Section 1, we find that Tarroja et al. (2012) and Ray et al. (2018) in their work have used a load model which is quite similar to the one used in the present paper with small peaks in the early morning and early evening hours. Flores et al. (2016) in their paper have estimated an exploitable solar potential of 18.68 TWh per year and 197.07 GWh per year of exploitable wind potential which are close in value to the current work. For the grid-connected case, the CUF of solar PV was assumed to be 25% which is also close to 22% used in the present. Khoie et al. (2019) in their paper on decarbonization of different geographical sectors of the US have given solar, wind and other renewable energy integration estimates that match the current values very closely. For instance, in the Middle West States continued utilization of wind (and other renewables) was expected to provide 120,000 GWh/year of surplus electricity in this region in 2050 which is of the same order of magnitude of the total renewable energy to be integrated into the southern grid of India as described in the present paper.

## 4. Discussion And Conclusion

A minute-by-minute analysis of matching electrical power availability from non-GHG sources with electrical power demand from South Indian electricity grid comprising five major states reveals several interesting points about the possibility of CO<sub>2</sub>-free electricity generation in this region:

- The current daily demand in these five states is of the order of 850 GWh of which at least 12 to 15% would be lost in the form of transmission and distribution losses.
- Existing wind, nuclear and hydro power generation amounts to about 341 GWh; using barren rocky waste land available for solar PV generation could generate a further 771 GWh, thus making 100% carbon-neutral electricity generation a possibility.
- The power consumption profiles over the day are such that nearly 36% of the power is needed in off-sunshine hours. This amounts to a total storage requirement of 311 GWh. Available stored form of electrical energy through large hydel plants in the five-state region is only about 100 GWh per day, leaving 211 GWh to be stored through other means. Accounting for storage losses (during charging and later discharging) leading to a round-trip energy efficiency at system level of 70%, the effective additional storage capacity would be about 301 GWh.
- Given that existing Pumped Hydro Storage schemes have a total capacity of only about 34 GWh, other means have to be found for about 267 GWh. Given that battery storage systems of the order of a few GWh capacity are already being planned or under construction in the US and China, and given the huge potential (in terms of scalability and cost, see Jensen et al. (2015)) of reversible solid oxide cell (ReSOC)-based storage systems, it is proposed to make up this additional capacity by having either battery or ReSOC systems located in selected districts having surplus energy.

- The present model results show that battery systems of total capacity of 57.6 GWh and ReSOC systems of 181.5 GWh will, together with existing PHS and hydro, meet the storage requirements for a 100% renewable + nuclear electricity generation for the Southern region of the Indian electricity grid.
- It is anticipated that the fairly large battery storage will be able to even out fluctuations in wind and solar energy over the day while the cheap energy storage capacity of ReSOC systems can be used to provide a buffer, of say, 500–1000 GWh for day-to-day fluctuations of wind and solar systems.

In summary, it can be concluded from the present study that it is feasible to operate the Southern sector of the Indian electricity grid through 100% non-GHG sources. Although, by way of illustration, the model has been applied for a specific day in mid-July, the model is flexible for application to any day of the year. Indeed, it is expected that power supply managers and policy makers will use it for several days over a year to optimize the location and size of the electrical energy storage units.

## Declarations

### Data Availability

*All data generated or analysed during this study are included in this published article*

### Funding

*The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.*

### Competing Interests

*The authors have no relevant financial or non-financial interests to declare.*

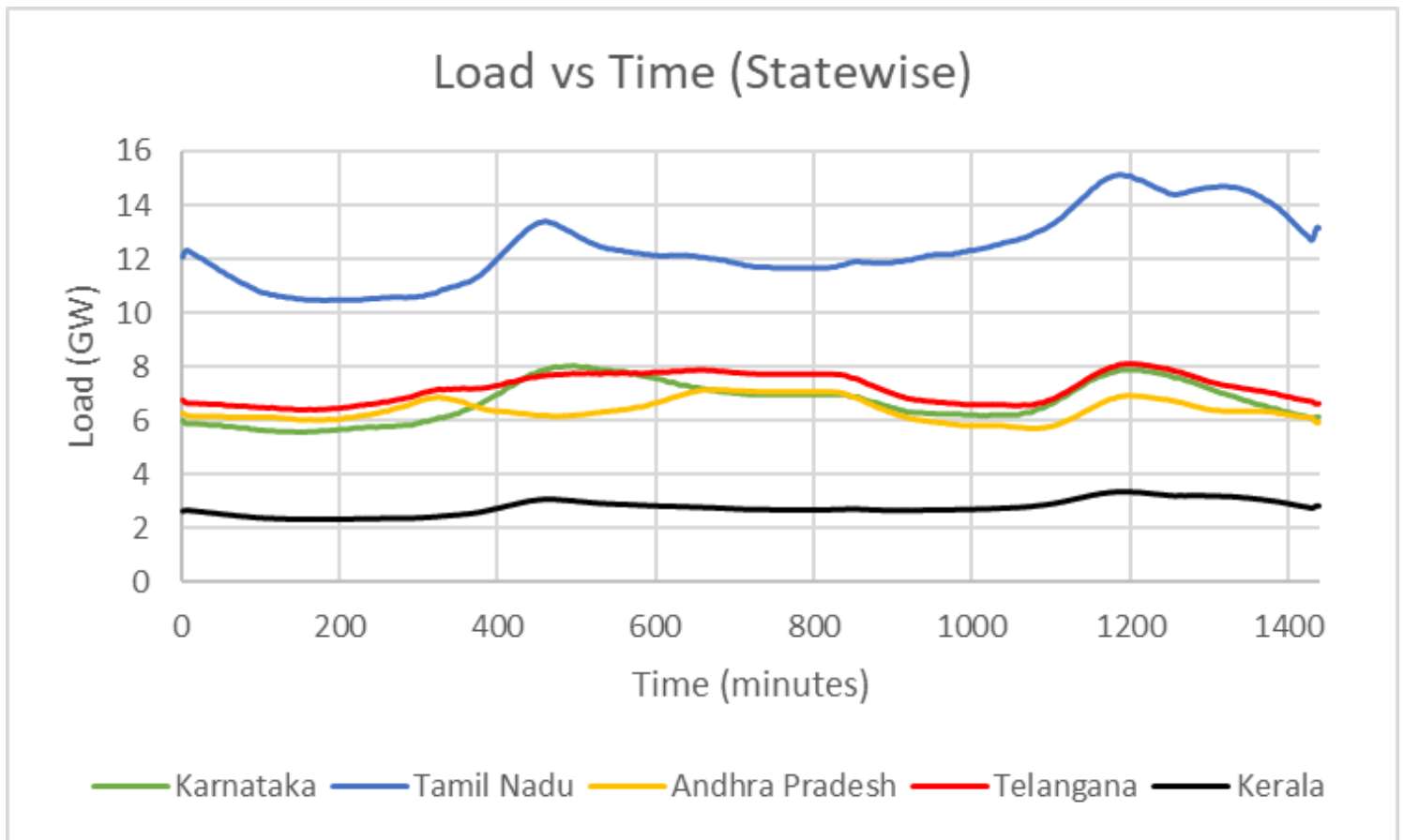
## References

1. Barelli L, Desideri U, Ottaviano A (2015) Challenges in load balance due to renewable energy sources penetration: The possible role of energy storage technologies relative to the Italian case. *Energy* 93:393–405. <https://doi.org/10.1016/j.energy.2015.09.057>
2. Boddapati V, Nandikatti ASR (2020) Salient features of the national power grid and its management during an emergency: A case study in India. *Energy Sustain Dev* 59:170–179. <https://doi.org/10.1016/j.esd.2020.10.010>
3. Buckley T, Shah K (2019) Report entitled “Pumped Hydro Storage in India: Getting the right plans in place to achieve a lower cost low carbon electricity market” of *Institute for Energy Economics and Financial Analysis*, Australia, March 2019; [https://ieefa.org/wp-content/uploads/2019/03/IEEFA-India\\_Pumped-Hydro-Storage\\_Mar-2019.pdf](https://ieefa.org/wp-content/uploads/2019/03/IEEFA-India_Pumped-Hydro-Storage_Mar-2019.pdf) accessed on 15th February, 2022
4. Çeçen M, Yavuz C, Tirmikçi CA et al (2022) Analysis and evaluation of distributed photovoltaic generation in electrical energy production and related regulations of Turkey. *Clean Techn Environ*

- Policy. <https://doi.org/10.1007/s10098-021-02247-0>
5. Dawoud SM (2021) Developing different hybrid renewable sources of residential loads as a reliable method to realize energy sustainability. *Alexandria Eng J* 60(2):2435–2445. <https://doi.org/https://doi.org/10.1016/j.aej.2020.12.024>
  6. Dong Z, Jiang D, Guo Z, Huang X (2020) Flexible Control of Nuclear Cogeneration Plants for Balancing Intermittent Renewables. *IFAC-PapersOnLine* 53(2):12560–12565. <https://doi.org/https://doi.org/10.1016/j.ifacol.2020.12.1813>
  7. Flores HFV, Furubayashi T, Nakata T (2016) Decentralised electricity generation system based on local renewable energy sources in the Honduran rural residential sector. *Clean Techn Environ Policy* 18:883–900. <https://doi.org/10.1007/s10098-015-1067-x>
  8. Golla M, Chandrasekaran K, Simon SP (2021) PV integrated universal active power filter for power quality enhancement and effective power management. *Energy Sustain Dev* 61:104–117. <https://doi.org/10.1016/j.esd.2021.01.005>
  9. Jensen SH, Graves C, Mogensen M, Wendel C, Braun R, Hughes G, Gao Z, Barnett SA (2015) Large-scale electricity storage utilizing reversible solid oxide cells combined with underground storage of CO<sub>2</sub> and CH<sub>4</sub> [10.1039/C5EE01485A]. *Energy Environ Sci* 8(8):2471–2479. <https://doi.org/10.1039/C5EE01485A>
  10. Khoie R, Ugale K, Benefield J (2019) Renewable resources of the northern half of the United States: potential for 100% renewable electricity. *Clean Techn Environ Policy* 21:1809–1827. <https://doi.org/10.1007/s10098-019-01751-8>
  11. Kumar A, Jayanti S (2021) A land-use-constrained, generation–transmission model for electricity generation through solar photovoltaic technology: a case study of south India. *Clean Techn Environ Policy* 23:2757–2774. <https://doi.org/10.1007/s10098-021-02202-z>
  12. Laugs GAH, Benders RMJ, Moll HC (2020) Balancing responsibilities: Effects of growth of variable renewable energy, storage, and undue grid interaction. *Energy Policy* 139:111203. <https://doi.org/https://doi.org/10.1016/j.enpol.2019.111203>
  13. Liu L, Senjyu T, Kato T, Howlader AM, Mandal P, Lotfy ME (2020) Load frequency control for renewable energy sources for isolated power system by introducing large scale PV and storage battery. *Energy Rep* 6:1597–1603. <https://doi.org/https://doi.org/10.1016/j.egyr.2020.12.030>
  14. Mah AXY, Ho WS, Hassim MH et al (2022) Spatial optimization of photovoltaic-based hydrogen-electricity supply chain through an integrated geographical information system and mathematical modeling approach. *Clean Techn Environ Policy*. <https://doi.org/10.1007/s10098-021-02235-4>
  15. Martin A, Agnoletti M-F, Brangier E (2020) Users in the design of hydrogen energy systems: a systematic review. *Int J Hydrogen Energy*. <https://doi.org/10.1016/j.ijhydene.2020.02.163>
  16. Monie S, Nilsson AM, Widén J, Åberg M (2021) A residential community-level virtual power plant to balance variable renewable power generation in Sweden. *Energy Conv Manag* 228:113597. <https://doi.org/https://doi.org/10.1016/j.enconman.2020.113597>

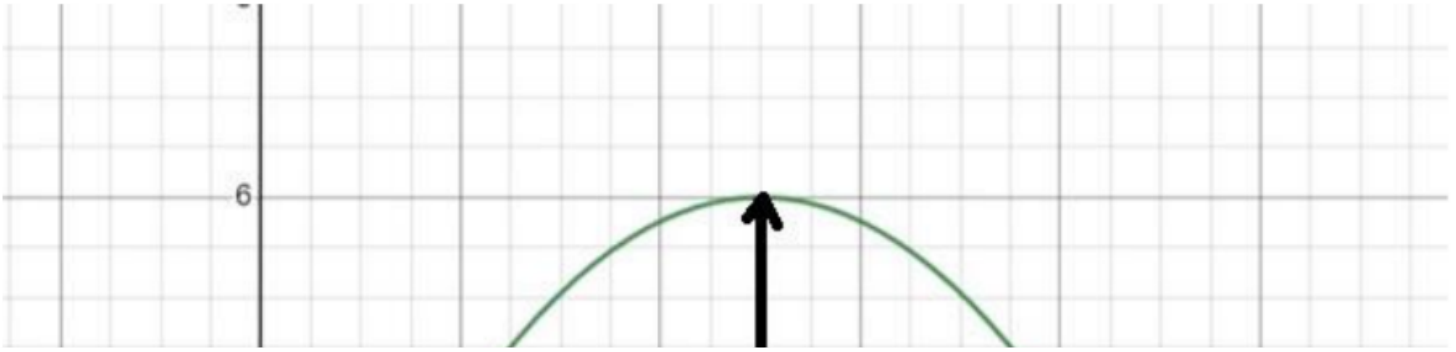
17. Nikolaidis P, Poullikkas A (2018) Cost metrics of electrical energy storage technologies in potential power system operations. *Sustain Energy Technol Assess* 25:43–59.  
<https://doi.org/10.1016/j.seta.2017.12.001>
18. Ogunjuyigbe ASO, Ayodele TR, Monyei CG (2015) An intelligent load manager for PV powered off-grid residential houses. *Energy Sustain Dev* 26:34–42.  
<https://doi.org/https://doi.org/10.1016/j.esd.2015.02.003>
19. Oldenbroek V, Wijtzes S, Blok K, van Wijk AJM (2021) Fuel cell electric vehicles and hydrogen balancing 100 percent renewable and integrated national transportation and energy systems. *Energy Convers Management: X* 9:100077. <https://doi.org/https://doi.org/10.1016/j.ecmx.2021.100077>
20. Palchak D, Ehlen JCA, McBennett B, Milligan M, Deshmukh IC, Abhyankar N, Soonee SK, Narasimhan SR, Joshi M, Priya Sreedharan (2017). GREENING THE GRID: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. II—Regional Study. National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Power System Operation Corporation, and the United States Agency for International Development., Vol. II
21. Ray A, Jana K, Assadi M et al (2018) Distributed polygeneration using local resources for an Indian village: multiobjective optimization using metaheuristic algorithm. *Clean Techn Environ Policy* 20:1323–1341. <https://doi.org/10.1007/s10098-018-1562-y>
22. Sarker E, Seyedmahmoudian M, Jamei E, Horan B, Stojcevski A (2020) Optimal management of home loads with renewable energy integration and demand response strategy. *Energy* 210:118602. <https://doi.org/https://doi.org/10.1016/j.energy.2020.118602>
23. Tarroja B, Mueller F, Eichman JD, Samuelsen S (2012) Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing. *Energy* 42(1):546–562. <https://doi.org/https://doi.org/10.1016/j.energy.2012.02.040>
24. Wang L, Zhang Y, Pérez-Fortes M, Aubin P, Lin T-E, Yang Y, Maréchal F, Van herle J (2020) Reversible solid-oxide cell stack based power-to-x-to-power systems: Comparison of thermodynamic performance. *Appl Energy* 275:115330.  
<https://doi.org/https://doi.org/10.1016/j.apenergy.2020.115330>

## Figures



**Figure 1**

Variation of load in GW for various south Indian states as a function of time over one whole day starting from midnight (adapted from Palchak et al., 2017).



**Figure 2**

Variation of solar insolation power (in GW) during the sunshine hours modeled as a parabola;  $T$  is the time duration between time of sunset and time of sunrise and  $H$  is the maximum power generation rate.



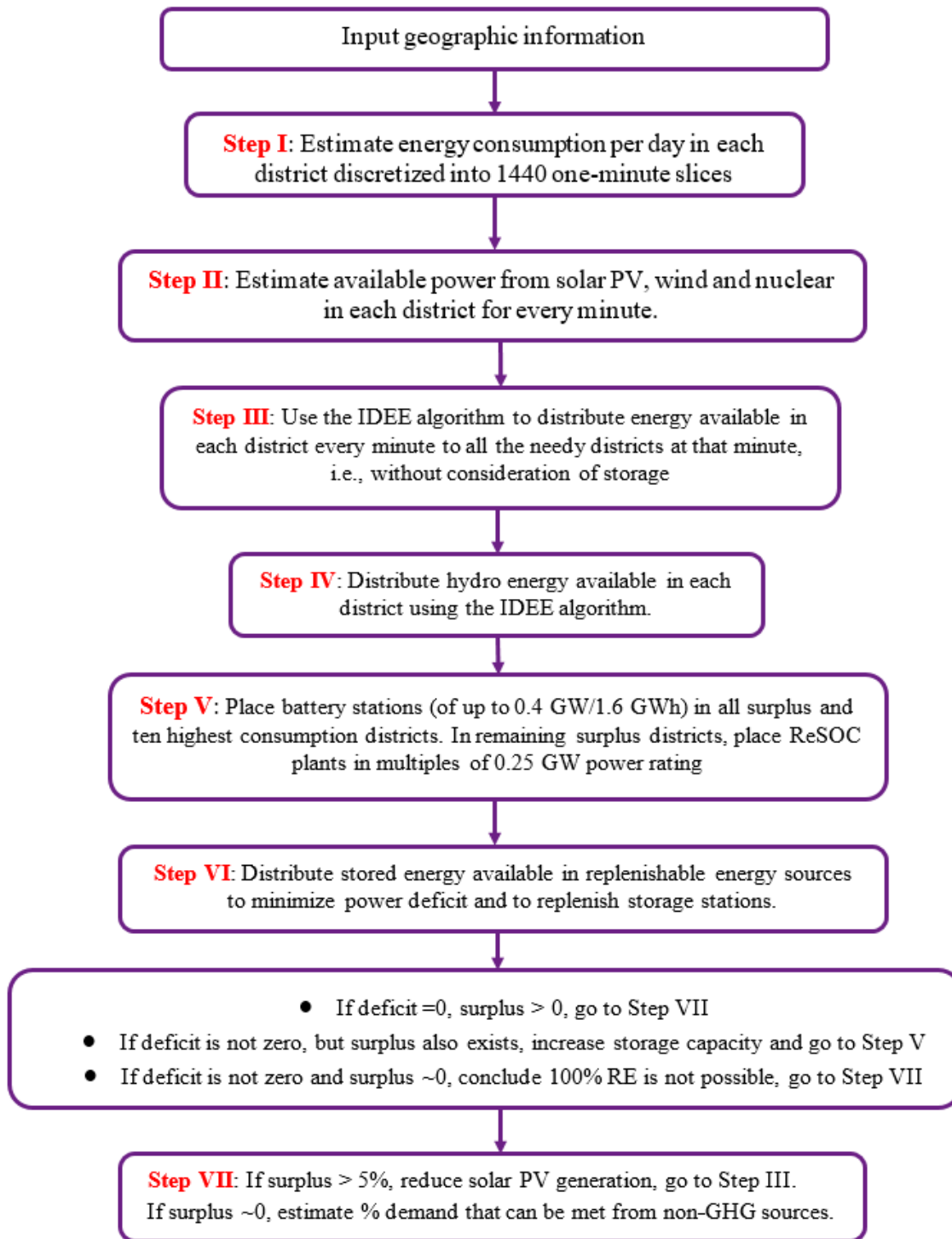


Figure 3

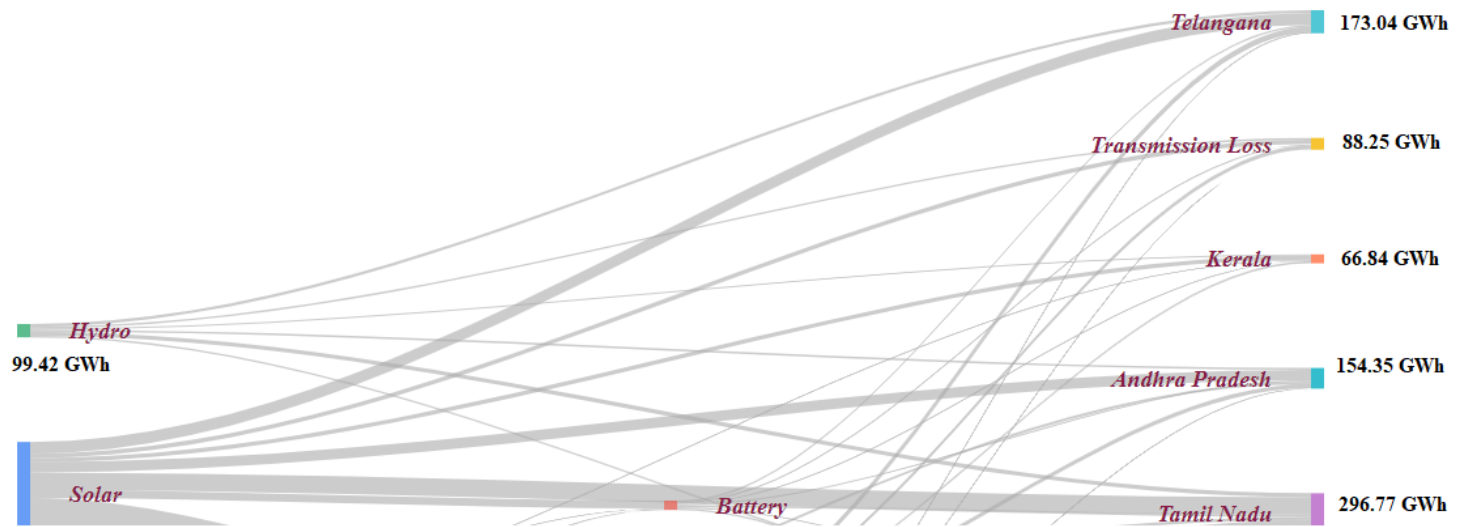
Flowsheet of the energy allocation steps.

Figure 4

Normalized state-wise consumption of electricity over a day in the five states. (b) . Electricity consumption in each district on the chosen day. (c) to e(iii) Daily availability of solar PV, wind, nuclear, pumped hydro and hydro energy generation in the five south Indian states.

**Figure 5**

(a) Typical deficit profiles for districts, and (b) distribution of replenishable energy sources . The numbers in the map correspond to serial numbers in Table 2.



**Figure 6**

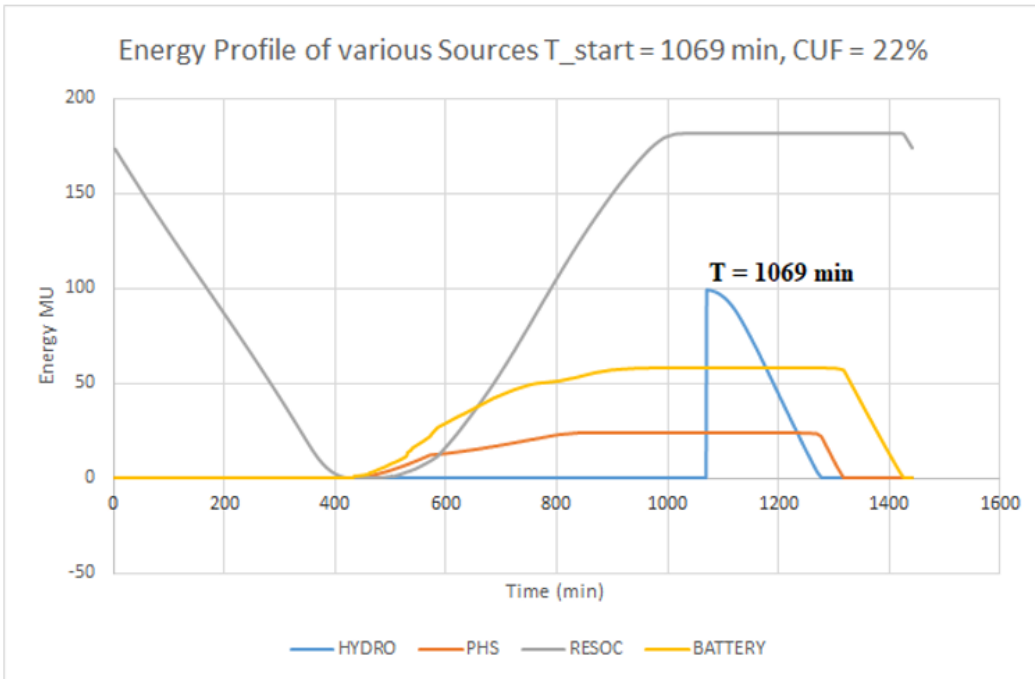
Overall energy flows among the various components of the model. Further details of energy flows from different perspectives are described in Figures 7 and 8.

**Figure 7**

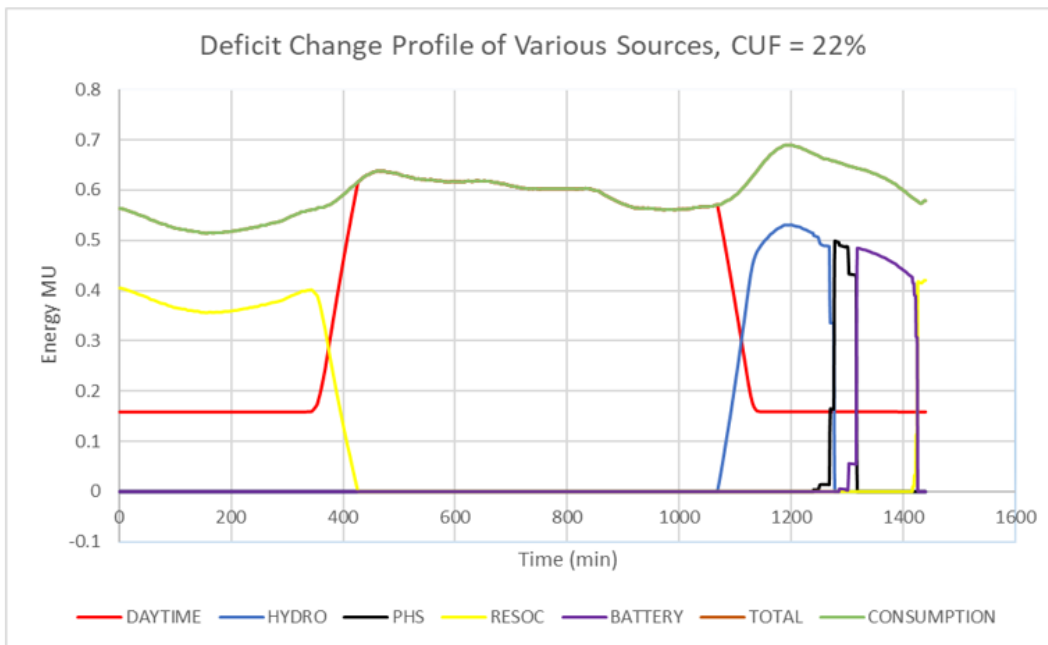
Energy flows from the four primary power providers to the five South Indian states, replenishable sources and transmission loss.

### **Figure 8**

Cumulative electrical energy delivered over the day to the five major states of South India from various power sources including the three replenishable energy storage devices.



A



B

Figure 9

(a). Predicted deployment over the day of the various energy sources. (b). Minute-by-minute net power deficit change over the day for all the five states put together