Analysis of Large-Scale Energy storage options for the interconnected electricity system in the Indian Subcontinent

Karthik Subramanya BHAT, Udo BACHHIESL

Institute of Electricity Economics and Energy Innovation, Graz University of Technology

Abstract: In the context of ushering in a Renewable Energy transition, tremendous changes are expected in the coming few years in regional electricity sectors in the Indian subcontinent region. As seen by many as a positive change, the underlying challenges in the regional electricity systems could lead to several new complexities with the integration of a large capacities of Variable Renewable Energy (VRE) in these regional electricity systems. Inadequate and inefficient inter-regional and intra-regional transmission infrastructure, insufficient energy storage options, and access to sustainable financial investments are few of these above-mentioned underlying challenges. Large scale energy storage (LES) technologies have been widely identified as one of the key technologies for the sustainable renewable energy integration by the global energy community.

With a large share of the VRE capacity proposed in the Indian electricity sector, in accordance with the United Nations Framework Convention for Climate Change (UNFCCC) [1] agreements and the Sustainable Development Goals (SDG 2030) [2], the requirement for LES capacities in the Indian electricity system is significantly large. The situation of energy storage options in the Indian electricity sector presently is very insignificant, with pumped hydro storage amounting up to 5 GW and few battery storage installations in the Mega Watt range [3]. However, in the next few years, plans to improve the LES capacity up to 20 GW (14 GW pumped hydro and 5.8 GW battery storage) [4] have been proposed, at significant locations throughout the country. In this paper, a scenario is built around the improvement of LES and VRE in the Indian Subcontinent, and is simulated using the techno-economic simulation model ATLANTIS_India, developed at the Institute of Electricity Economics and Energy Innovation, Graz University of Technology. A wide range of simulation results varying from transmission load flows to the annual electrical energy generated have been used to evaluate the scenario and provide several conclusions to the said strategy

Keywords: Energy Storage, Renewable Energy, Sustainable Transition, Indian Subcontinent

1 Introduction

The Indian subcontinent can be considered almost the size of EU27, in terms of both area and population. It is also recognized as one of the faster developing regions in the global economic and energy sectors, especially due to the rapid industrialization and development of economy. The electricity demand growth rates in the region are observed to be significantly higher than the globally observed average, compounded with the high carbon intensities of the regional electricity sectors, which, along with a strong commitment towards a renewable energy shift, make the region significantly interesting to the international energy community. The impact of energy transitions in the electricity sectors of the Indian Sub-continent region could significantly reduce the energy related emissions- observed even on a global scale, and hence a significant boost to the efforts by the global community in the battle against climate change is to be expected. Though several commitments to the UNFCCC and the SDG 2030 have already pushed the region to significantly improve the renewable energy shares in their respective electricity sectors, with further motivation and support from the international community, an accelerated growth in renewable energy capacity in the region is to be expected.

2 Energy storage in the Indian subcontinent

The energy situation in the Indian sub-continent region is characterized mainly by the Indian electricity sector. Though the Indian electricity sector interacts significantly with the other regional sectors in the sub-continent region, the larger changes in the Indian electricity sector have been observed to significantly impact the overall energy situation in the region. Several electricity sectors like Nepalese and Bhutanese electricity sectors have seen significant improvements and investments by the Indian electricity sector in the recent few years. These investments in the region are a result of change in energy policies of India, and these electricity sectors have also benefited from the situation. Though there definitely exists a large potential in the regions of Nepal and Bhutan for Pumped Hydro Power storage installations, the only large-scale energy storage options in the sub-continent region currently are found in the Indian electricity sector.

On the cusp of an energy transition, the Indian electricity sector is poised to overcoming several challenges in the transition process. Several positive developments in the last few years indicate the Indian electricity sector's efforts to ready itself for the big shift to Renewables from conventional power generation. There has been a tremendous increase (from 83 percent in 2015 to ~98 percent in 2019) [5] in the access to electricity rates, with further improvements and expansions in high voltage and distribution network infrastructure. An almost hand-in-hand improvement of large capacities of renewable capacity (excluding Large hydro power installations) has been achieved through the form of several lucrative subsidies for private investors. The large-scale new installations and further expansions of existing Solar Photo Voltaic (PV) and Onshore wind capacities were also achieved in a relatively short duration of time. Small-scale hydro power installations were timely and conveniently subsidized to such an extent that the improvement of private investments in this sector have increased significantly in almost every region in the country.

However, the electricity sector, even with the new improvements, still depended upon coal fired capacities to provide up to 55 percent of the total annual electricity generated in 2019 [5] This is mainly due to the arising requirement of coal-fired capacities to compensate the relatively frequent and seasonal fluctuations in the generation by the renewable energy fleet. The transmission infrastructure/ grid components have a higher number of complex interactions to balance out the intermittent generation from the VRE capacities, thus leading to an 'underutilization' of the VRE power plant fleets. The improvement of transmission infrastructure could be one solution, but with the interconnected transmission network covering a tremendous area in the sub-continent region makes this option severely expensive and time consuming. The other possible option to manage such a situation would be to have a proportional energy storage capacity installed across the country in relation to the installed VRE capacities. The situation in the Indian sub-continental transmission grid completely highlights the massive role large scale energy storage technologies play in a grid with high VRE penetration.

2.1 Energy storage in India

Large scale Energy Storage (LES) in the Indian sub-continent is observed to be mainly implemented in the Indian electricity system. However, energy storage in India has clearly not been prioritized until recent times [6], mainly due the electricity sector prioritizing on base-load generation technologies like coal and gas power. The dependence on base-load generation technologies gradually developed in the 1990s, mainly to sustain the ever-growing electricity demand of the economic development process in the country. Over the recent commitments India has to the global community, and the electricity sectors of India and subsequently its neighbouring countries are experiencing a gradual shift to renewable energy (Especially VRE technologies). In support the expansion of VRE capacities, the Government of India (GoI) has now quite an ambitious but highly necessary strategy to increase the energy storage capacities in the Indian power plant fleet in the coming decade. The Table (1) details the existing energy storage capacities installed by the year 2019, and also the proposed expansion of energy storage capacity, mainly pumped hydro power and battery storage capacities until the year 2040.

Status (values in MW)	**Pumped hydro storage**	**Battery storage**	**Total**
Existing (2019)	5757	125	5882
Proposed (until 2040)	8900	5000	13900
Total	14657	5125	**19782**

Table (1) LES existing capacity in India and planned expansion strategy (for India) [3][4]

Currently, a cumulative PSP capacity of over 5.75 GW exist, and a further improvement of 8.9 GW is planned to be installed gradually until the year 2040. Subsequently, over 5 GW of battery storage capacities (mainly at large solar PV installations sites) are also planned to be implemented, along with the implementation of the expansion of renewable energy shares until the year 2040 [7]. The energy regulators in the country have yet to devise a national strategy to implement large scale battery storage in the urban infrastructure of the country, which is also predicted to be significantly necessary both in the integration of VRE capacity in the county, along with the implementation of the nation-wide electromobility strategies.

From the Table (1) it can be observed that LES capacity in India has mainly been Pumped Storage Power plant (PSP) capacities until recent years. The expansion of large-scale battery storage capacities has been almost completely ignored, and only a few test plants and pilot projects form the small 125 MW of the battery storage capacity in the country. Interestingly, in the residential and the industrial demand sectors, there exists a large number of small-scale battery storage capacities of Uninterrupted Power Supply (UPS/Inverter) systems distributed almost across the country, among almost every upper-class and middle-class households, along with small- to medium-scale industries. This is mainly due to the long-term implementation of several load management strategies like load shedding by regional transmission system operators in view of the insufficient generating capacities. This somehow forms a small share of the decentralized storage capacity in India, and manages to slightly bring down the existing demand supply gap. Large industries usually prefer to install their own gas turbine power plants, for an uninterrupted heat and electricity supply. The above mentioned de-centralized small-scale energy storage has been implemented as a decrease in the electricity demand of several model regions, for the sake of simplicity in the course of this study.

3 Techno-economic simulation model ATLANTIS_India

ATLANTIS_India [8] is a techno-economic model developed for the Indian sub-continent region at the Institute of Electricity Economics and Energy innovation (IEE), Graz University of Technology. The work surrounding the development of the model was elaborate, considering the highly specific technical details and the geographical accuracy involved within. The model is closely based on the techno-economic model ATLANTIS [9], also developed at IEE, for the simulation of the Pan-European energy economics. The model ATLANTIS_India covers the five different power regions in India: East Region (ER), North East Region (NE), North Region (NR), South Region (SR) and West Region (WR), along with the regions of Bangladesh (BA), Bhutan (BH), Nepal (NP) and Sri Lanka (SL). These four power regions/ countries have close interaction with the Indian electricity system.

The model is characterized by a physical technical layer, along with an economic layer, thus making it a techno-economic model. The physical layer consists of technical elements like demand centres/nodes, transmission lines, transformer stations, power plant park and several other components of the power system. ATLANTIS_India consists of more than 3000 nodes with node-specific demand distribution, over 6200 transmission lines with physical restrictions, and over 4000 powerplants with different technology types and their specific parameters like efficiency, availability factors and ownership company information. Furthermore, the additional demand resulting from electromobility strategies can also integrated in to the model, if and when necessary. The physical elements defined in the model are as visualized as shown in the Figure (1).

The simulation mechanisms included in ATLANTIS_India are based on four different market models – the basic Copper-Plate 'Stock market' model, the 'Zonal Pricing' model, the 'Total market' model and the 'Re-dispatch' market model. The 'Stock Market' model assumes a huge copper plate on which the model regions lie, so no restrictions to power exchange between regions is assumed. The 'Zonal Pricing' model includes Net Transfer Capacity (NTC) based trading restrictions in to the basic 'Stock market' model. This market model brings in an NTC based market coupling between all the model regions, where the maximum export/import between regions is decided by the NTCs between the regions. The 'Total market' model includes load flow calculations but ignores the NTC restrictions between model regions.

The 'Re-dispatch market' model, is the most complex and the most realistic market model type in ATLANTIS_India, with the inclusion of load flow calculations and Net Transfer Capacity (NTC)-based trading restrictions between the regions. The Re-dispatch market also follows an NTC-based market coupling approach, but with the inclusion of physical transmission restrictions within the regions. The market coupling between the model regions is designed for a zonal approach, and is based on an implicit auction mechanism.

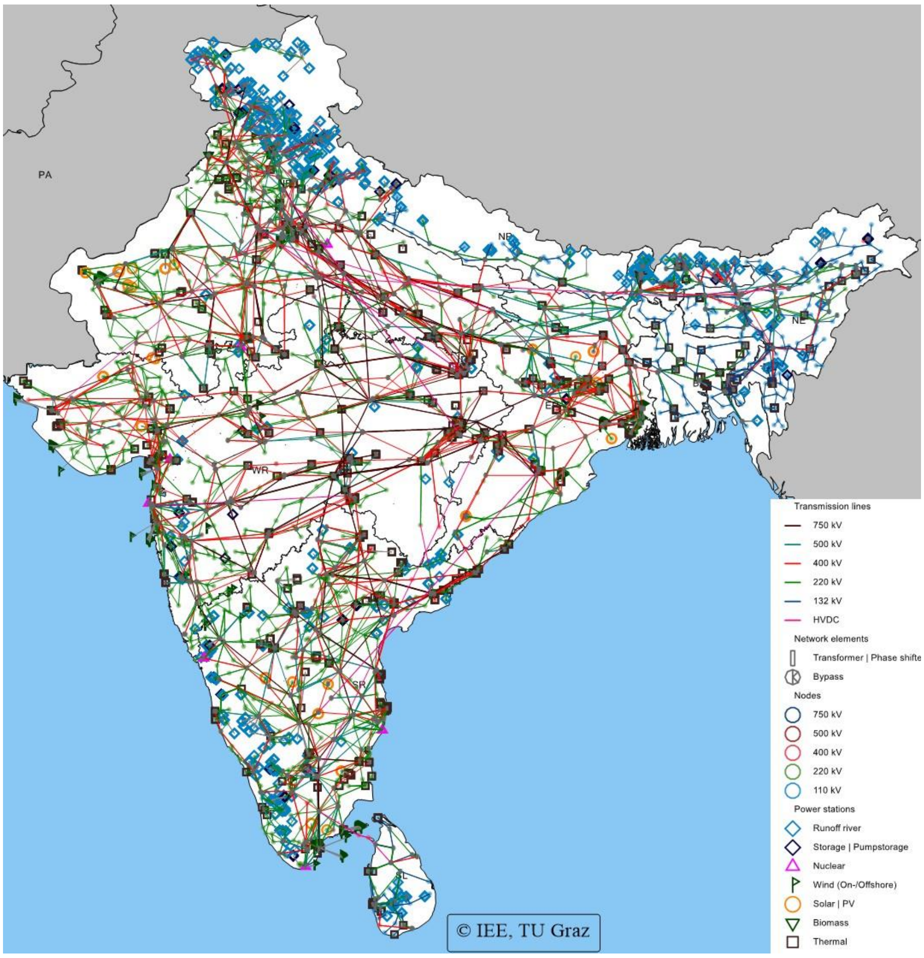

Figure (1) Visualization of the physical layer in the simulation model ATLANTIS_India

The main results of the market coupling are unit dispatch, the import-export balances of each bidding zone, and the zonal prices of the electricity. In the subsequent step, the market model results and the resulting dispatch are evaluated in terms of load flow calculations based on DC-load flow (DC-OPF method) [9]. The DC-OPF method has been proven to be effectively useful in the simulation of large and complex networks [10].

The Re-dispatch market model, like all the other market models in ATLANTIS_India, follows a cost-based optimization procedure. In the Re-dispatch market model, along with the NTC based market coupling algorithm (cross border constraints), the objective function is defined as the maximization function for the social welfare- by minimization of overall generation costs, from an electricity economics perspective. The maximization function can be described as follows.

$$\max_{qD,qS}\left\{\sum_i\left[\sum_n(qD_{n,i}\cdot pD_{n,i})-\sum_a(qS_{a,i}\cdot c_{var}S_{a,i})\right]\right\}$$

$$\begin{aligned}
s.t.\ & qS_{a,i}\le qS_{max_{a,i}}\\
& qD_{n,i}\le qD_{max_{n,i}}\\
& export_{i\rightarrow j}-import_{i\rightarrow j}\le NTC_{i\rightarrow j}\qquad \forall(i,j|i\neq j)\\
& \sum_k export_{k\rightarrow j}-\sum_k import_{k\rightarrow j}\le TP_{k\rightarrow j}\qquad (k\subset i\wedge j\notin k)\\
& \sum_a qS_{a,i}-\sum_n qD_{n,i}+\sum_{i\neq j} import_{i\rightarrow j}-\sum_{i\neq j} export_{i\rightarrow j}=0\qquad \forall i
\end{aligned}$$

with:

i, j:	bidding zones, market areas
k:	defined technical profiles between market areas
n:	block bid of demand
a:	block bid of supply
$qD_{n,i}$:	cleared part of demand block n in market i (MW)
$qS_{a,i}$:	cleared part of supply block a in market i (MW)
$pD_{n,i}$:	demand price (€/MWh)
$c_{var}S_{a,i}$:	marginal costs of supply block a in zone i (€/MWh)
$import_{i\rightarrow j}$:	import in market i from market j (MW)
$export_{i\rightarrow j}$:	export from market i to market j (MW)
$NTC_{i\rightarrow j}$:	net transfer capacity between market i and j (MW)
$TP_{k\rightarrow j}$:	technical profile between marketset k and j (MW)

For the scope of this paper, the RDZP market model type is used to simulate an as-close-to-reality-as-possible scenario for the defined RE and Energy storage strategy, for the Indian subcontinent until the target year 2040.

ATLANTIS_India also features Capital Stock calculations for power plant fleet evaluations, Profit and Loss statements and Financial balances for over 200 defined power plant owner companies. The economic evaluation also strives to be realistic, with the inclusions of time series of several factors like interest rates, inflation rates, depreciation rates, primary energy price indexes and many more economic parameters in the calculations. These Capital Stock evaluations can be really useful, especially with the implementation of large additions of PSP capacities, which have larger technical useful lifetimes. The capital stock evaluations mainly highlight the long term social and economic benefits to the Indian electricity system, and help in the further planning and implementation of other sustainable strategies.

4 Study Scenario

The scenario defined in this paper deals mainly with the expansion of VRE capacity and the LES capacities in India, in order to analyse several techno-economic effects on the overall electricity system. Around 118 GW of VRE capacity additions to the Indian power plant fleet have been introduced, including the refurbishment of RE capacities (at the end of their technical lifetimes) within the target year 2040. Overall, a total of 88 GW of solar PV and 30 GW of on- and off-shore wind capacities forms a large share in the Indian power plant fleet, in the year 2040 [11]. Similarly, as per the published national strategies, a cumulative PSP capacity of 8.9 GW and a Battery storage capacity of 5 GW have also been implemented. These added capacities are exclusive of the already existing and implemented 5.7 GW of PSP and 0.125 GW of Battery storage capacity. The several challenges [12] to the expansion of large hydro and PSP in India are assumed to be already addressed, and all the planned PSP projects in the national strategy are implemented. The geographic information of the planned

PSP projects was taken from various sources, from government reports, project reports and published articles. However, the 5 GW of planned battery storage capacity was implemented by distributing 100 MW of capacity at the several identified planned and existing VRE capacities.

The Figure (2) shows the visual representation of the study scenario, highlighting the tremendous increase of VRE capacities like Solar PV and Onshore wind, and the subsequent smaller increase of the share of the 'Pumped storage' shares. For the sake of simplicity, the Battery storage capacities are defined in the power plant input data in a similar way as the PSP capacities, albeit with the variation generation pattern (PSPs are assumed to generate mainly during peak load).

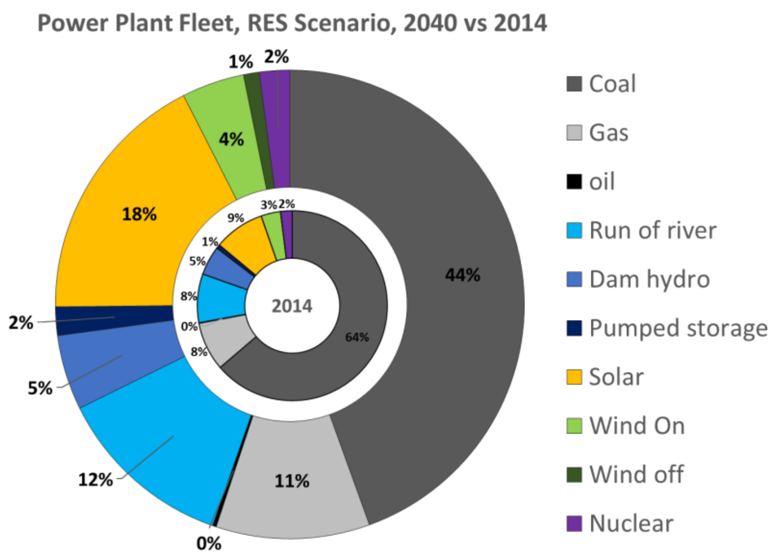

Figure (2) Visualization of the power plant portfolio evolution in the study scenario until the target year 2050

5 Results

The designed study scenario is simulated using ATLANTIS_India until the target year 2040 and the several results are discussed. Over a multitude of possible simulation results, the load flows in the transmission network and the re-dispatch occurring due to the transmission bottlenecks are used to evaluate the scenario simulations in this paper. The analysis of these results provides us an overall understanding of the system performance in the simulated scenario. Furthermore, only the simulation results for the month of August, where the yearly demand peak is known to occur, has been analysed.

The Figure (3) shows the visualization of the simulated load flows in the transmission network in the 'Peak_a' period in the month of August 2040. Several transmission bottlenecks are observed (highlighted as dark red) around the locations of the planned VRE capacities and as well as the planned and existing LES capacities. The Battery storage capacities, which are planned subsequently near the feed in nodes of the implemented VRE expansion, have relatively insignificant bottlenecks around their planned locations, in comparison with the transmission network around the pumped hydro units. The bottlenecks in the transmission system is observed in the 220-kV infrastructure around the VRE capacities, and in the case of PSP capacities, the bottlenecks are observed to be mainly in the 400-kV transmission network.

This is understandable, as almost all of the PSP units are defined to feed in at 400-kV transmission level suited for long distance transmission. The concentration of the bottlenecks in the 220-kV level are found to be higher in the NR, WR and the SR regions respectively.

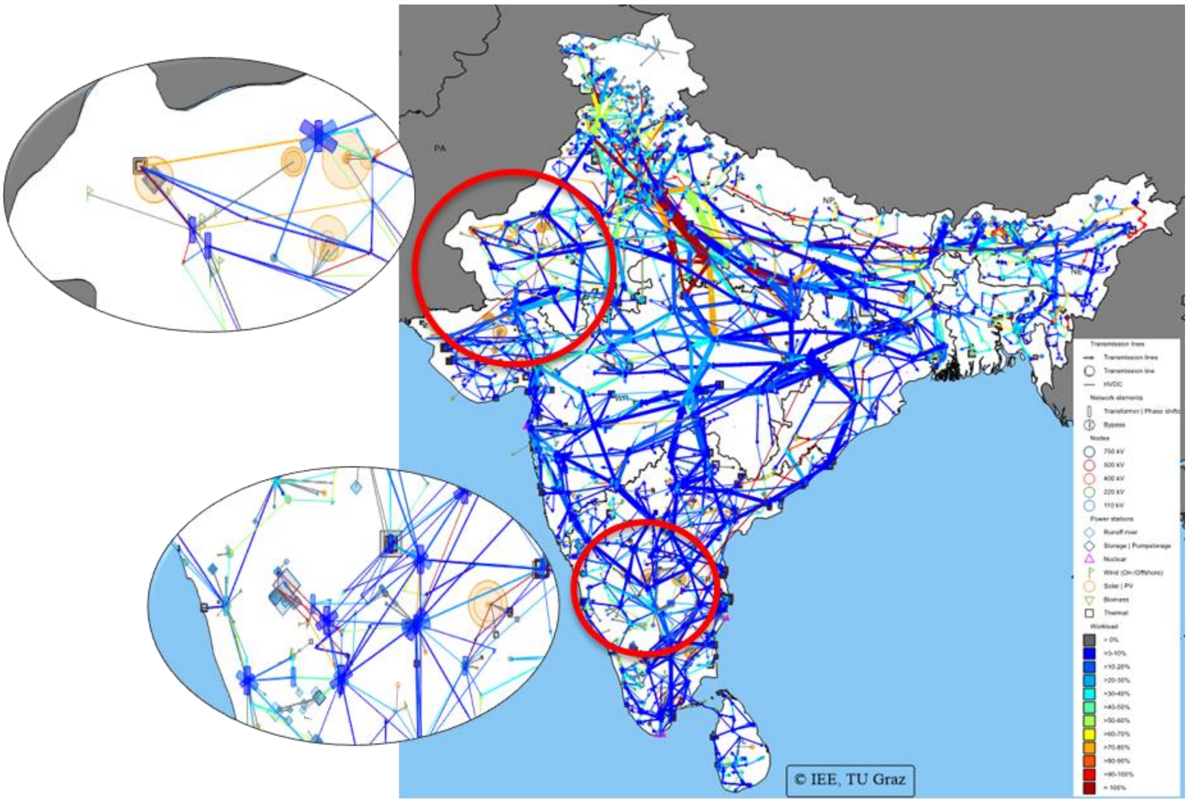

Figure (3) Load flow simulated in the transmission network, for the period 'Peak_a' in August 2040,

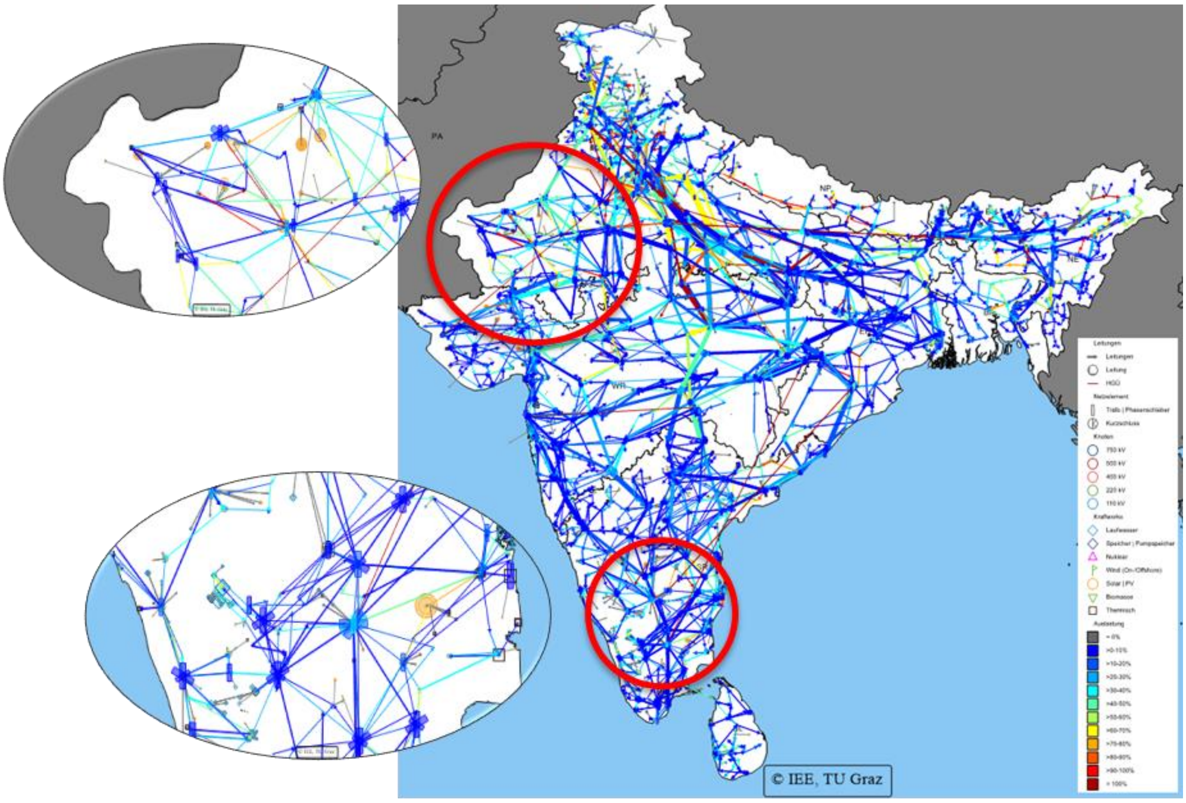

Figure (4) Load flow simulated in the transmission network, for the period 'Offeak_a' in August 2040

Similarly, the simulated load flows for the ‘offpeak_a’ period are also analysed for the month of August 2040, to see if there are observable changes to the transmission load flow in the system. As seen in the Figure (4), the observed transmission bottlenecks are seen to be mostly eased, especially around the PSP units, at the 400-kV level transmission network. However, the bottlenecks in the NR and SR region at the 220-kV transmission levels around the battery storage capacities and VRE (especially wind) are still observed.

Another perspective to the analysis of the system effectiveness would be to compare the simulated electrical energy generated by the various power plant types, and to check if there is an under/over utilization of the capacities due to redispatch. A look at the annual electrical energy generated by the power plant fleet shows an overall decreasing trend in the electrical energy generated by coal and gas-fired capacities until the target year 2040. The comparison of the share of annual electrical energy generation by storage capacities with the various power plant technology types in the power plant portfolio of the Indian sub-continent (Figure (5i)) gives us a measure of the effectiveness of the storage capacities planned. A significant increase in the generation by storage capacities is observed beginning from the year 2025 when most of the planned PSPs are assumed to begin operations. However, in comparison to the large increase in solar PV and wind shares in the power plant fleet as seen from the scenario description, the increase in the respective shares of electrical energy generated seems to be not that significant.

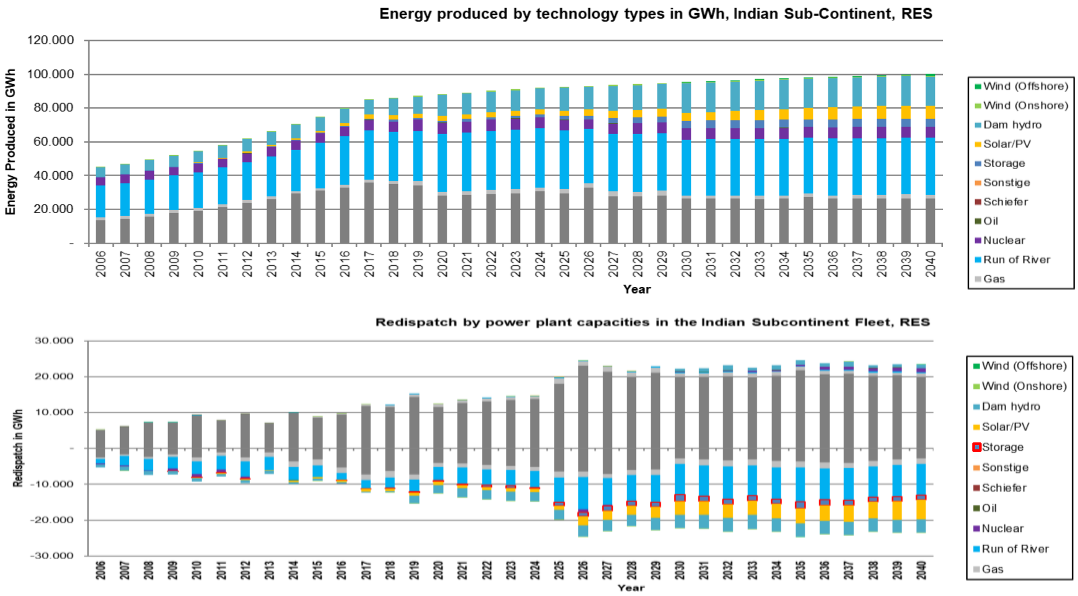

Figure (5) The shares of annual electrical energy produced by power plant technology types (above) and the decreased generation by Storage capacities mainly due to redispatch resulting from transmission bottlenecks (below)

However, when the increased (positive redispatch) / decreased generation (negative redispatch) occurring due to redispatch is analysed (Figure (5ii)) it is observed that there is a definite underutilization (decreased generation) by storage and VRE capacities, compensated by an increased generation by coal- and gas-fired capacities. This is also confirmed by the transmission bottlenecks observed in the load flow visualizations before, as redispatch is the result of these occurring bottlenecks.

6 Conclusions

The overall implication of the strategy implemented in the study scenario shows a considerable decrease in the energy generated from conventional coal and gas-fired power plant fleet in the Indian sub-continent region. However, several conclusions have been inferred, and improvements suggested, based on the evaluations of the simulation results in the course of the study.

Primarily, the amount of planned LES expansions seem insignificant, in comparison with the overall increase in VRE capacities until the year 2040. The national strategy for energy storage must be revised to implement a much higher capacity of energy storage facilities planned. A decreased usage of the planned VRE capacities are seen to occur, also due to the observed absence of sufficient storage capacities. Thus, more emphasis on energy storage planning has to be provided, in the planning and designing of the Indian national strategy. A strategy to utilize the enormous potential in the regions of Nepal and Bhutan has to be drafted, for the subsequent integration of the said VRE expansions and long-term sustainability.

Additionally, strategic reinforcement and expansion of transmission infrastructure at the 220-kV level has to be implemented, for the successful and more effective integration of the planned VRE capacities (mainly around the planned Solar PV capacity). Similarly, strategic reinforcement or expansion of the 400-kV transmission infrastructure has to be also implemented, especially around the feed-in nodes of the planned PSP capacities. This reinforcement and/or expansion of transmission infrastructure would relieve the bottlenecks observed around these planned VRE and LES capacities, and improve the generation and the overall effectiveness by decreasing the redispatch occurring due to the observed transmission bottlenecks. The observed under-utilization of the VRE and LES capacities are for now compensated by an increased generation by coal and gas-fired capacities, which defeats the point of the devised strategy to reduce the carbon intensity of electricity generation in the sub-continent region. Thus, transmission infrastructure planning also takes priority, along with the emphasis on the LES capacity expansion.

With long term sustainability, social and economic welfare of the several regional electricity sectors in mind, the capital stock evaluations of power plant fleets have to be conducted. With larger technical lifetimes, PSP capacities easily become major contributors to the capital stock of the respective regional power plant fleet. If India does consider to invest in the exploitation of PSP and large hydro potentials in the regions of Nepal and Bhutan, a significantly large increase in the capital stocks of the electricity sectors of Nepal and Bhutan regions can be expected. With the added share of generation capacities to their electricity sectors, and through the economic benefits from capital stock increase and trading in the future, several improvements to the electricity sectors in these regions can be made possible. This would definitely bring about social and economic welfare in the region, contributing to the welfare in the overall sub-continent region. Thus, promotion of PSP as the LES option has to be prioritized, as many regional systems in the Indian sub-continent would gain large long-term technological and economic benefit.

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