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Techno-economic analysis of development scenarios for the electricity economy of the Indian subcontinent region

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AFFIDAVIT

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“ गुरुर्ब्रह्मा गुरुर्विष्णु र्गुरुर्देवो महेश्वरः |

गुरु साक्षात परब्रह्मा तस्मै श्रीगुरवे नमः ||”

‘The Guru (Teacher) is Brahma (Creator), is Vishnu (Protector), is also Maheshwara (Lord Shiva),
The Guru is undoubtedly the Supreme-Being, Salutations to that Guru’

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Kurzfassung

Die zunehmende Besorgnis über die katastrophalen Auswirkungen des Klimawandels hat im Laufe der Jahre verschiedene Länder auf der ganzen Welt dazu veranlasst, weitgehend in klimafreundliche Technologien zu investieren. Mehrere Studien [1][2] stimmen folgernd überein, dass ein Anstieg der globalen Durchschnittstemperatur von mindestens 2°C bis 2050 zu erwarten ist, wodurch die Entwicklung weitaus bedenklicher als bisher angenommen ist. Dieser Anstieg der globalen Durchschnittstemperatur ist hauptsächlich auf die sogenannten Treibhausgasemissionen zurückzuführen. Der globale Energiesektor leistet einen wesentlichen Beitrag zu den gesamten Treibhausgasemissionen und fast 40% dieses Anteils stammen aus der Stromerzeugung. Die Emissionen im Zusammenhang mit Energiebedarf und Stromerzeugung steigen aufgrund der rasanten Industrialisierung und wirtschaftlichen Entwicklung insbesondere in Entwicklungsländern wie Indien und China unkontrolliert. Der Energiebedarf und die wirtschaftliche Entwicklung in diesen Ländern sind stark miteinander verbunden [2], wodurch selbst geringfügige Änderungen ihrer Elektrizitätssysteme schwerwiegende Folgen für die Entwicklung der Volkswirtschaften haben könnten.

Der indische Elektrizitätssektor ist weltweit bekannt für seine Abhängigkeit von Kohle zur Stromerzeugung. Im Jahr 2018 waren rund 57% der gesamten installierten Kapazität des Landes Kohlekraftwerke [3], die zu über 65% zur Jahresstromerzeugung beigetragen haben. Das jährliche Wachstum der Stromnachfrage hat sich in Indien in kurzer Zeit exponentiell erhöht. Darüber hinaus befindet sich das indische Elektrizitätssystem (a) aufgrund verschiedener globaler Verpflichtungen in Bezug auf den Klimawandel [6] und der SDG2030 (b) in einem enormen Wandel hin zu erneuerbaren Energien wie Photovoltaik und Windkraft. Die Integration großer Mengen dargebotsabhängiger sowie volatiler Erzeugung aus erneuerbaren Energien in das bestehende Elektrizitätssystem erfordert eine rechtzeitige und strategische Planung, da sonst schwerwiegende Komplikationen im alternden Elektrizitätsnetz des Landes zu erwarten sind, welche in weiterer Folge auch Konsequenzen für die verschiedenen miteinander verbundenen regionalen Elektrizitätssysteme der Nachbarländer haben können. Techno-ökonomische Simulationen sind daher essentiell, um das Verhalten derartiger miteinander verbundener Elektrizitätssysteme im Übergang zu alternativen Energietechnologien und der strategischen Planung zukünftiger Energieprojekte in der Region besser zu verstehen.

Das am IEE der TU Graz entwickelte ATLANTIS_India [7] ist ein einzigartiges techno-ökonomisches Simulationsmodell, welches die Untersuchung von Entwicklungsszenarien der Elektrizitätswirtschaft am indischen Subkontinent ermöglicht. Das Modell umfasst die fünf indischen Stromregionen sowie die Regionen Bangladesch, Bhutan, Nepal und Sri Lanka. Die Volkswirtschaften und die Elektrizitätssysteme in diesen Regionen haben bereits bedeutende Wechselwirkungen mit indischen Regionen, welche sich künftig noch intensivieren werden. Das physikalische Modell besteht aus den erforderlichen technischen Komponenten wie Knoten, Leitungen, Kraftwerken und Transformatorstationen. Für die Marktsimulationen können unter Einbeziehung von Unternehmensbilanzen, Gewinn- und Verlustrechnungen sowie Kapitalstockberechnungen vier verschiedene Marktmodelle verwendet werden. Im Rahmen dieser Arbeit werden vier verschiedene Evolutionsszenarien für den indischen Subkontinent definiert, die jeweils die unterschiedlichen langfristigen Zielsetzungen untersuchen. Ein breites Spektrum an Simulationsergebnissen wie Lastflüsse im Übertragungsnetz, erzeugte elektrische Energie, resultierende CO2-Emissionen, Zonenpreise oder die Entwicklung des Kapitalstocks werden detailliert ausgewertet und je Szenario werden spezifische Schlussfolgerungen für die nachhaltige Entwicklung der Elektrizitätswirtschaften am indischen Subkontinent abgeleitet.

Abstract

Increasing concern over the catastrophic effects of climate change over the years has led several countries across the globe to largely invest in climate-friendly technologies. With several studies [1][2] conclusively agreeing that an increase in the global average temperature of at least 2°C by the year 2050 is to be expected, the situation is far worse than previously thought of. This increase of average global temperature is mainly due to the so-called Green House Gas (GHG) emissions. The global energy sector makes a significant contribution to total GHG emissions, with nearly 40 percent of this share coming from electricity generation. Emissions related to energy usage and electricity generation are growing uncontrollably due to rapid industrialization and rapid economic development in 'developing' countries such as India and China. The energy usage and the economic development in these countries are observed to be strongly coupled [2], which would mean that even minor changes in their electricity systems could have serious consequences on the development of their economies.

The Indian electricity sector is known globally for its dependence on coal-fired facilities for electricity generation. By 2018, around 57% of the country's total installed capacity were coal-fired capacities [3], which generated over 65% of the total electricity generated annually. With the improvement in electricity access rates in the country [4], the annual electricity demand growth in India has increased by an exponential factor in a short duration of time. Furthermore, with various global commitments with respect to climate change [6](a) and with global sustainable goals (b), the Indian electricity system is undergoing an enormous transformation towards alternative renewable energy technologies like solar PV and wind power. When a large penetration of such Variable Renewable Energy (VRE) technologies is executed with insufficient planning and haste, severe complications can be expected to occur in the country's aging transmission grid and the overall electricity system in general. These complications could also have serious consequences for the several interconnected regional electricity systems of the neighboring countries. Therefore, strategic planning is needed for the sustainable development and the successful transition of such electricity systems. A techno-economic simulation model could be very useful in understanding the behavior of such interconnected electricity systems in between a transition towards alternative energy technologies, and in the strategically planning of futuristic energy projects in the region.

ATLANTIS_India [7] is a unique techno-economic simulation model developed at the IEE, TU Graz. The simulation model is specifically designed to simulate the electricity economics in the Indian subcontinent region. The model covers the five Indian power regions, along with the regions of Bangladesh, Bhutan, Nepal and Sri Lanka. Without serious political conflicts, the economies and the electricity systems in these regions already have /are expected to have several significant interactions with Indian regions. The physical layer of ATLANTIS_India consists of several technical components –demand center/ nodes, transmission lines, power plants and transformer stations. Four different market model types are used for market simulations, with the economic layer consisting of financial balances, profit and loss statements and capital stock calculations for the model regions. Four different evolutionary scenarios are defined in the scope of this thesis for the development of the electricity system in the Indian subcontinent, each examining the different long-term goals set by the regulatory authorities in the region. A wide spectrum of simulation results like load flows in the transmission grid, electrical energy generated, resulting CO2 emissions and zonal prices are evaluated in detail, and scenario specific conclusions are derived.

CHAPTER 1

The Indian Electricity Economics

1. Introduction

The energy systems in the world today is in transition into clean and renewable energy, due to increasing concern and awareness over climate change and pollution. While most of the developed (industrialized) countries show a saturation in electricity demand, several developing economies like India and China face a demanding challenge - managing to sustain their economic growth with rapid increase in electricity demand. Along with reducing the overall energy related emission, RE capacity expansion has always been India's best solution to address the challenge of exponential growth in electricity demand. India has proposed to install 175 GW of solar PV and wind power by the year 2025 [3][6], in order to achieve complete energy access and to inherently and significantly reduce the carbon intensity of its energy sector. Though the plans seem entirely over-optimistic, if and when achieved, would solve most of the country's energy-related problems.

India is a country globally well known for its diversity, geographical and demographic size, culture and many other things. On the other hand, the country is also known for its massive energy related emissions. An overview of the primary energy usage in India deeply highlights the role of fossil fuels, mainly coal and oil. Most of the electricity in India comes from coal-fired power plants, while the share of renewables in the electricity generation mix are comparatively less (around 12 percent) [3]. Moreover, the Indian fossil fuel balance shows that there is an absolute import dependency of the country for both coal and oil, implying a direct relation to the country's economy. Considering the steep growth in the industrial and economic sectors, increasing population and an improvement of electricity access rates, a large-scale expansion of generating capacity is necessary to ensure complete energy access.

Covering of just the base load became a major priority to the Indian electricity system, to support the rapid industrialization and the resulting economic growth in the country. 'Base load' generation in India since a few decades has been done by coal-fired thermal power plants, given their high reliability and cheap electricity generation prices. Base load power plants are those which can be relied upon for a steady, continuous supply of electricity for a specific duration of time. In the past, several possibilities for nuclear generation capacities to take up the role played by coal-fired capacities were considered in detail. However, this strategy could not be effectively realized even after several attempts, due to several roadblocks related to Non-Proliferation and nuclear trade. India never had any global obligations related to energy related emissions (disagreement to the Kyoto Protocol), so there was never really a problem for the country to expand its cheapest generating capacity - Coal.

However, with several other developments over the decade, the country has realized its responsibility in the global effort to battle climate change. India agreed to curtail over 30 percent of its energy related emissions by 2030, and to the Sustainable Development Goals (SDGs). With several commitments now to the global energy community, the country has to plan the transition from generation by its fossil fuel capacities to generation from cleaner sources like RE and hydro power. The possibility to consider a transition can be justified by the availability of (more than sufficient) technical potential for RE generation and the significant interest of the Indian policy makers in an energy transition. Though the mind-set of the country's power sector still seems to be inclined towards coal being never replaced by any technology in the near future, many initiatives like subsidy and support schemes [9], energy-savings initiatives and other energy efficiency improvement [10] strategies have been proposed, in support of the much-needed energy transition. These initiatives ensure reductions in the demand growth rates, while in turn also assuring a possibility of large-scale renewable electricity generation to take up the role of coal-fired generation. However, a high penetration of VRE technologies in the electricity system could result in severe complications and system complexities, with regards to their fluctuating generation, unpredictable nature in availability and lower reliabilities.

India's most suitable solution for a sustainable VRE integration could be to include several Large-scale Energy Storage (LES) capacities, which involves the building of highly capital-intensive infrastructure usually with large geographical dependencies. This could be the greatest challenge to the financially riddled Indian power sector, as the building of new infrastructure would not only require more capital, but also lead to the stranding of already installed capital intensive coal and gas fired infrastructure assets. Faced with several challenges, India has to design and implement several long term energy plans, all the while ensuring the country's economic progress and growth. Therefore, a sustainable strategy for the effective integration of large RE penetration in the electricity system has to be carefully designed. To validate such a long term sustainable strategy, the evaluation of the tecnological and economic impacts in the region is absolutely necessary.

India along with the countries of Bangladesh, Bhutan, Myanmar, Nepal, Pakistan and Sri Lanka can be grouped together with the name Indian Sub-Continent. The regional economics and the electricity sectors of several of these interconnected neighboring countries are also closely related to the Indian economy and energy sector. Though India shares its largest border with Pakistan, due to several political and territorial conflicts, the interactions between the two electricity sectors have been unfortunately almost close to none. The electircity systems of Bangladesh, Bhutan, Nepal and Sri Lanka though, have several interactions with Indian electricity system. The countries of Nepal and Bhutan have been historically on good terms with India for the development of infrastructure and other commodity trades. The generation capacities in these countries already support the secondary peak coverage in the East and North power regions in India, with several already exisitng cross-border transmission infrastructure. It has also been widely speculated, through the means of many bi-lateral agreements, that the Indian electricity sector will eventually have more interactions and interdependencies with the these neighboring electricity sectors in the coming future. Thus, it is justified to consider the evolution of the complete electricity system in the Indian Sub-Continent region, while planning a sustainable strategy for the transition process towards green energy. In this doctoral thesis, a techno-economic model specifically designed to simulate the electricity economics of the Sub-Continent region has been introduced, and four different evolution scenarios have been defined, simulated and evaluated.

1.1. India: A Brief Overview

India is a large country, both in terms of area and population. The country has an area of 3.3 million sq. km and a population of 1,324 billion, as of the beginning of the year 2019 [11]. India can almost be compared with the area of the EU 27 countries, so the extent of diversity in geography, energy usage and availability of resources can also be appropriately imagined [12]. India has different climate zones, with respect to its large geographical area. To the south near to the equator is much of a tropical climate zone, to the west is a dry temperate climate, a completely temperate climate in the central region, and temperate tundra in the north and the north east of the country closer to the Himalayan mountain range. Furthermore, seasonal variations in temperature and rainfall is also different in different regions, within a given year. For example, when there is the ‘wet’ rainy season in the south, you can expect a dry season in the north. Such complexity in resource availability by climate zones, along with many other factors, makes the energy situation of the country far more interesting to analyze than many.

India, though being termed as a third world economy, or even as a developing economy, plays a major role in the global economic scenario. The country has the fifth highest Gross Domestic Product (GDP, BIP) annually in nominal values, surpassing several countries like France and The United Kingdom. The current GDP of India as of 2018 has been published as a worth of 2900 Billion US $, by the World Bank [13]. However, due to its immensely large population, the GDP per capita comes to a considerable smaller amount of 2015.4 US $, for which it doesn't even get a mention in the top 20 countries. India is projected to be the world's most populated country in the end of 2020, overtaking China with a projected population of 1.4 billion. The country's GDP per capita, along with the primary energy consumption per capita, is increasing at a substantial rate, as the economic development is closely coupled with energy use. Also, India, along with Africa would host almost half of the world's population by the year 2030 [14]. With increasing energy consumption in Africa too, it would mean an immense increase in the primary energy consumption of the two regions, when looked at from a global perspective. The Indian share of global primary energy consumption is expected to rise from 6 percent in 2018, to almost 11 percent in the year 2040 [15], with an estimated increase in population of 400 million and an almost tripling of the country's economy. The primary energy demand in India, classified with respect to fuel types is as seen in the Figure (1). This situation, along with the rapid growth in industrial manufacturing sector of the country, would make it one of the major players in the global energy sector within the next few decades.

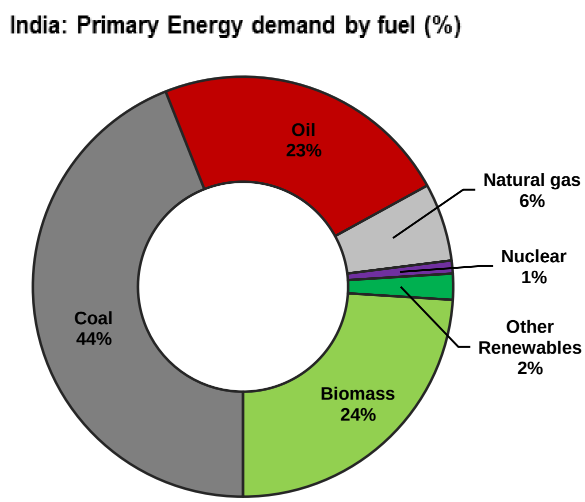


Figure (1) Primary energy demand, by fuel type shares [*Source: WEO2015*, IEA]

The situation is not only of concern for the country, but also is a concern on a global context, as the amount of energy related GHG emissions in India are almost directly linked to primary energy usage, and the country's share of emissions being significantly large in the global emissions sector. Surely, since the electrification of almost all sectors in the western countries, i.e., domestic (cooking), heating and more, the proportion of the emissions related to the use of primary energy has considerably decreased. However, with a large country like India, with several challenges already in its electricity sector, the electrification of all the domestic sectors could be practically impossible. A complete electrification of the country's large transportation sector would almost be next to impossible, considering that around 35 percent of the primary energy consumption is taken up by this sector. Thus, the electricity generation sector in India, where there are several but much simpler challenges, has to be sustainably transformed from its current state to a minimum emissions sector to reach India's long-term sustainability targets.

2. The Indian Electricity Sector

India’s energy demand has almost doubled since the year 2000, with a large share of the increase related to its electricity consumption. The energy sector in India today is completely unrecognizable from the one that existed few decades ago, especially because of the major economic reforms in the early 1990s [3][16]. The economic boom in the following years lead to a rapid industrialization and urbanization which in turn led to the increase in the electricity demand, forcing the country to expand its lagging generation capacity. The subsequent results of these economic reforms and rapid industrialization plunged the country into a ‘base load- mentality’, where you give the highest priority to cover only the base load in an energy system. Such thinking can lead to serious repercussions, especially concerning long term sustainability of an energy system. The situation for base load coverage was so critical, that the energy politics of the country at one time only concentrated on covering the industrial load, which almost completely formed the base load of the country. To maintain the operations of the industrial sector was rigorously worked upon, to keep the economic progress on track. Cheap power generation grade coal was abundantly available, both domestic and imported. In comparison to the other electricity generation technologies, the cost of electricity generation from imported coal-fired generation technology was/is still the least expensive. This led to the unchecked and continuous addition of coal-fired capacities, year after year.

The partial liberalization of the energy/ power market by the Electricity Act of 2003 [17] also played its part, by giving the private investors in the Indian electricity sector complete freedom to invest in generation capacities, and sell electricity over a single platform. The consequences of these events led to the situation today - the electricity sector dominated by the fossil fuels like coal and gas-fired technologies. Coal-fired power plant capacity occupies the largest share of 57 percent in the Indian installed capacity mix, followed by hydropower at 15 percent. A Figure (2) shows the installed capacity mix in the Indian electricity system, in September 2019.

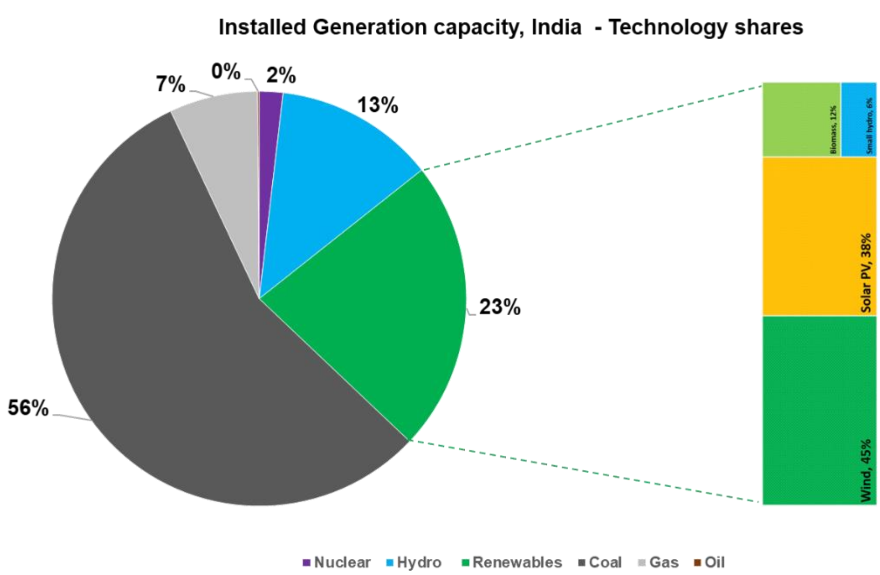


Figure (2) Classification of Installed capacity in India, as on 30.09.2019 [*Source: CEA, GoI, 2019*]

The implications of the recently proposed industrial and economic policies, notably ‘Make in India (2015)’ campaign, would mean a huge increase in the electricity demand of the manufacturing sector, similar to the situation in the 1990s. As Industrial electricity consumption forms almost 45 percent of the country’s overall electricity consumption [12][18], this would mean a tremendous generation capacity addition would be required within the next few years. In accordance with the agreement at the UNFCCC COP21 (a) summit held in Paris in 2015, and the Sustainable Development Goals (SDG 2030) (b) set by the United Nations (UN), India has set up emission curtailment targets and agreed to introduce a larger share of RE to diversify the electricity generation portfolio of the electricity sector, and to provide access to clean energy. However, such a huge change cannot be successfully achieved, in the relatively short time-frame agreed upon (2030). Hence, definition of initial priorities to use 'cleaner' and much more efficient conventional energy generation technologies have been suggested by several studies conducted by the Government of India (GoI). These priorities focus upon the implementation of Carbon Capture and Storage (CCS) technologies, Super critical boilers, Combined Cycle Gas Turbine technology and 'clean coal' technologies. Although a few of the proposed policies still stay focused on coal-fired generation, the GoI has decided to focus on another area, one that should have been focused upon in the early 2000s- diversification of the Indian power plant portfolio, especially by including a large share of RE technologies. The GoI and the Ministry of power (MoP) have ambitious targets for RE integration in the Indian electricity sector. Though faced by many challenges, the MoP is still confident that it can attain its target of 175 GW of solar PV and Onshore wind capacities by the year 2025.

The Indian electricity sector has several parameters that differentiate it from most of the other global electricity sectors. Like many other developing countries (ex. BRICS countries), the country's economic development is strongly coupled with the energy use. Small variation of oil prices by the OPEC and natural gas prices by exporting countries create large variation in the prices of commodities in the country. However, considering the available/ installed power plant capacity, India is among the leading countries eclipsing most of the 'developing' countries, with an installed capacity of 363.3 GW in the end of the year 2019. The population of the country is so huge, that even with such a large installed capacity, there are almost up to 30 million people without any access to electricity [4].

With the enormously increasing population and economic development, the electricity demand also has a staggering growth every year. The growth rate of annual electricity demand was observed to be as high as 6.3 percent in the years 2010-2013. This, when coupled with the insufficient capacity expansion has resulted in a demand-supply gap in the country's electricity sector. With insufficient generation capabilities, as discussed before, covering at least the base load (50 percent of the electricity demand) has since a long time been one of the main priorities of the Indian electricity sector. The simplest solution to overcome the demand-supply gap, though temporary, would be to add more generation capacities of the cheapest electrical power source in the country- coal. This exact 'temporary solution' led to the dominance of coal-fired electricity generation in the Indian electricity sector.

The seasonal variations in electrical load observed on a regional level, do not show up on the overall electrical load at the national level. The overall variations in the Indian electricity demand are thus not that prominent, which makes it relatively easier to cover the load with the same set of power plant technologies. Thus, in comparison to base load coverage, power plant portfolio diversification was never really a priority for the country, only until a few years back. It has to be noted that load is a characteristic of electricity demand, rather than a necessity of the supply side [19]. The corresponding Figure (3) illustrates the yearly variations in electrical load in the year 2011, as an example.

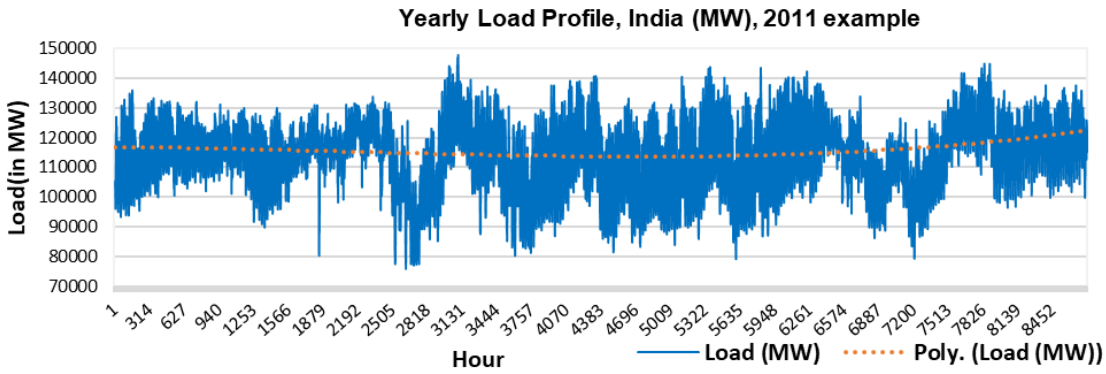


Figure (3) Electrical Load profile for the overall country for the year 2011. [*Source: CEA, GoI*]

The transmission network in the Indian electricity system is large and expansive, covering almost all the mammoth area of the country. The grid transmission and distribution system in India, including the inefficient and loss-making distribution companies (DSOs), and their associated lack of enforcing the Renewable Purchase Obligations (RPOs), is one of the key bottlenecks constraining the electricity sector. Furthermore, the huge investment required and the already available debt of the power sector present a complex situation to the GoI. The GoI believes that it can tackle the problem of financing by efforts to access International financing. Overall, the GoI's target of 100 GW of Solar PV and 75GW of wind power capacity by 2025 seems to be overly ambitious, with all the roadblocks and challenges in mind. As already discussed, the electricity sector of India is already in severe financial debts due to losses in Transmission and Distribution (T&D) network, and unorganized maintenance. In 2012, a 22 percent loss in T&D was recorded, which would mean that the supplying utility would have to produce more than one extra unit to satisfy a demand of five units [20]. The GoI should take up the task to improve the T&D network before the addition of new RE power plant capacity.

However, the identified renewable potential in India is so high that the technical potential of Solar PV alone can help meet its energy needs. The identified potential is so lucrative that the other challenges observed in the country's electricity sector seemingly feel insignificant. The framework for the addition of RE capacities has already been prepared by the GoI, by introducing Renewable Purchase Obligations (RPO) for investing companies with every new thermal power capacity added in several of the power regions in the country. Additionally, to promote RE power expansion in few of the power regions, the GoI introduced that all new thermal power plants (private or central) should plan and accommodate an additional renewable energy plant for at least 10 percent of its generating capacity. The energy market in India has also introduced Renewable Energy Certificates (RECs) mechanism, to promote and support the obligatory RPO measure. The GoI has recently initiated a radical transformation of the domestic coal mining, power generation, renewable energy and electricity distribution sectors.

The GoI has also ascertained that to attain such a radical transformation, energy efficiency will certainly be the key factor. Therefore, several Energy Efficiency directives have been proposed by the MoP and GoI. Furthermore, plans for the completion of many 'stopped' (construction paused due to capital investment issues or water sharing problems) hydro power plants in the North East power region, which is rightly named the 'power cradle of India' is also under way. Thus, it can be agreed that there exists a unique situation in the Indian electricity sector.

2.1. Variable Renewable Energy

The RE share in the Indian electricity sector has been classified separately from Large hydro power installations, thus RE expansion in India is largely focused on Variable Renewable Energy (VRE) technologies like Solar PV and Wind power. India has a large identified potential for electricity generation from both solar and wind resources. The relatively recent addition in to the 'renewables' share in the capacity mix is the 'small hydro' capacities, which constitutes run-of-river hydro power plants less than a Mega Watt (MW) of capacity.

VRE sources in nature are highly fluctuating and variable in their availability. As discussed before, more than 800 GW of identified technical potential for solar PV in India can single-handedly be used to reach the country's energy needs. However, both the resource and eventually the electricity generated by Solar PV is highly fluctuating in nature, due to several uncontrollable factors such as cloud coverage, seasonal precipitation and many other such factors. Similarly, wind power also has higher fluctuations, as a small change in wind speeds introduce larger changes (by exponential factor 3) in power generated. This introduces more complexity into the already complex interplay of system components in the electricity system. To balance the electricity generation and to compensate for the resulting complexities in the grid, the so-called 'integration costs' are incurred. With larger VRE systems, higher integration costs are incurred, while on an isolated small scale, they are almost close to zero. With smaller fluctuations in generation and more availability and reliability, Dispatch-able Renewable Energy (DRE) sources like hydro power and biomass energy tend to have relatively lesser or almost zero integration costs [21].

The solar and the wind resource, however, is free of cost, i.e., variable costs for such VRE systems are almost non-existent. With over 150 GW of solar PV and wind installations planned in just over a decade, it becomes a major priority to deal with these integration costs before the situation goes out of hand (the electricity sector starts spending more money just to maintain the system operations), when one of the main reasons of the RE expansion was to reduce the costs in the electricity system. Several work-arounds for higher VRE penetration and optimized/minimized integration costs have been proposed by several studies [19][37]. Solutions of hybrid systems involving VRE capacity expansion with DRE technologies or gas turbine capacities with high flexibility and lower capital intensities have been recommended.

With lesser fluctuations in generation of power, the 'integration costs' also tend to decrease. Thus, DRE sources become more important, when introduced along with a large VRE penetration. Such technologies are usually capital intensive, but their usefulness over their lifetimes make them very valuable. Furthermore, DRE technologies like Hydro power usually have very long lifetimes of (in some cases) more than 100 years. Furthermore, a study [22] estimates that the Levelized Cost of Electricity generation (LCoEg) from solar PV generation in India would reach the same cost as power from imported coal by the end of the year 2019, and continue to decrease further due to the technology learning effect.

2.1.1. Variable Renewable Energy in India

As already discussed, India has a vast potential for VRE sources like solar PV, solar thermal, offshore and on-shore wind. Interestingly, these potentially rich areas are mostly evenly distributed across the country. The fact that the VRE and DRE potentials are observed throughout the country further cements the fact that complete renewable generation in India could be a possible future. As discussed earlier, with the consideration of only small percentage of available rooftop area and 3 percent of waste land area per region for usage, India has a calculated technical potential of 784 GWp for solar PV (c). This technical potential was calculated with only centralized PV addition in mind, with the complete exclusion of off-grid possibilities. The access to the electrical grid is also a major factor when calculating the utilizable potential in the country. Centralized and distributed grid connected strategies and de-centralized off-grid solar strategies are already sketched out by the Indian planning commission to meet the RE expansion targets planned for the next decade. Off-grid solar is mainly planned to ensure electricity access and decreased grid dependency of rural remote areas in several regions [23]. Wind energy potential in India, however, is observed to be concentrated mainly in the southern and western Indian regions, where the topology of the land creates a natural wind corridor. Several measurement stations and pilot projects testing the availability of wind, both onshore and offshore are already established, which could be further exploited. An installed capacity of 32,28 GW (2016) already feeds in 46011,52 GWh (2016-2017) in to the grid [24]. Several potentially rich regions are labelled as wind power development zones, where measurement, testing of wind speed availability, and construction of capacities is already underway. Offshore wind potential is limited to the south-eastern shore and the north western coast. Figure (4) shows the increasing trend in the capacity expansions of both VRE technologies observed in the Indian electricity sector, in the year 2013.

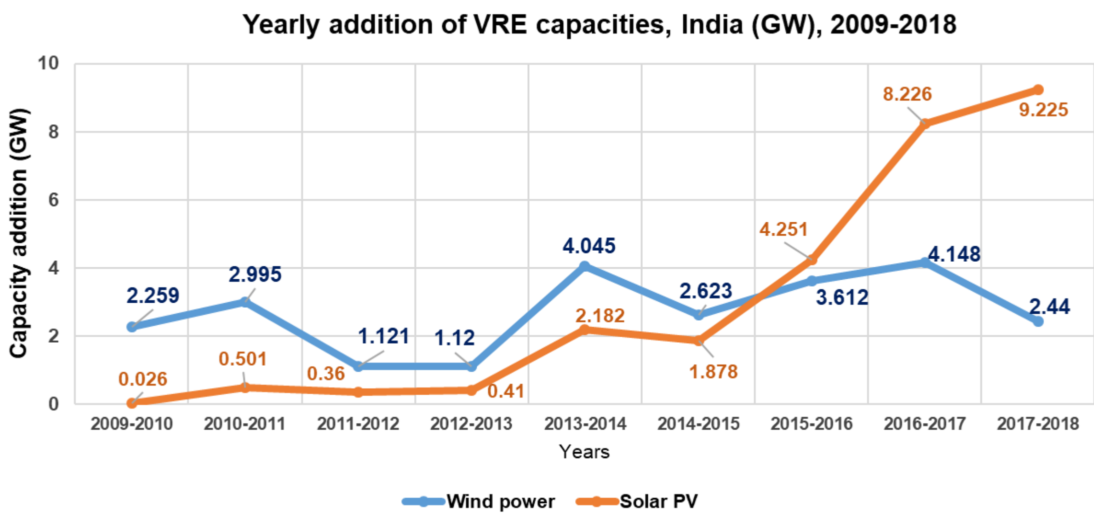


Figure (4) Solar PV and Onshore wind capacity addition in India, 2009-2018 [*Source: MoP, GoI*]

2.2. The Indian Power Plant Fleet

As of September 2019, India had a total installed capacity of 363.3 GW, with a significantly less diverse power plant portfolio. The diversification of the power plant portfolio is a recent initiative, to lose the absolute dependency of the country's power sector on imported coal. However, the 'base load' mentality in the country and its group of energy regulators, still creates and continues the situation where base load generation technologies are given immense importance (ex. coal). As discussed before, the country has a significantly large share of coal-fired capacity installed in its capacity mix, presently around 200 GW. However, the share of coal-fired technologies in the country is gradually decreasing with each year (63 percent in 2010 to 55 percent in 2019), with RE Sources (RES) gaining popularity based on the amount of subsidized promotion and support from the GoI. Furthermore, most of the coal-fired and gas-fired power plants in the Indian power plant fleet are relatively young, aging between a decade and/or two. Therefore, the share of electricity generated by coal-fired technologies is still significantly dominant, amounting to around 1200 GWh in 2016 [3][24].

With a country as large as India, large differences can be observed in the availability of energy resources and in turn the regional energy policies across the country. In some of the cases, even the cultural diversity has an impact on the regional energy policy making process. Energy regulation in India is carried out by state-owned regulation organization under the scrutiny of the central regulatory body, the Central Electricity Regulatory Commission (CERC). The keep the regulation process simple, based on several factors, the Indian power system is classified in to five different power regions – East Region, North East Region, North Region, South Region and the West Region. Similarly, each region has its respective state-owned Transmission System Operator (TSO) and Distribution System Operator (DSO) again under the supervision of the central regulatory body. These regional TSOs and DSOs work towards the construction and maintenance of their respective transmission and distribution grids. Therefore, planning of regional capacity expansion is usually done by the regional regulatory body, the central regulatory body supervises the process and sets specific regional goals for the regional regulatory bodies. There have been several observed and proposed changes to the regulatory process for electricity in India, especially after the introduction of the liberalized power and energy markets in the country.

Thus, the energy policies in the different regions vary significantly, but when summarized together, contribute to a single national goal. The uniqueness of the different power regions in India can also be seen by the classification of their respective power plant fleets. The power plant portfolio in specific regions and their fleet age structures in the study target year 2050 is as described.

2.2.1. East Region

The power plant portfolio of the East Region (ER) in India seems to be overly dominated by coal capacity, accounting to 86 percent of the total installed capacity. This is due to the availability of cheap domestic coal which is mined in the region, and also due to ease of access to trade of imported coal from the east (Indonesia) [25]. The regional power plant fleet plays a major role in exporting electricity to the demand rich regions like the West, South and the North power regions. A significant portion of the pie chart is also taken up by Hydro power plants, accounting to 12 percent of the overall installed capacity. However, hydro power expansion in the region has many challenges and road blocks even with the available untapped potential, since the region deals frequently with severe flooding in the rainy 'wet' season. A considerably smaller improvement in the solar power plant and wind capacity accounts for the 2 percent share of RES in the capacity mix.

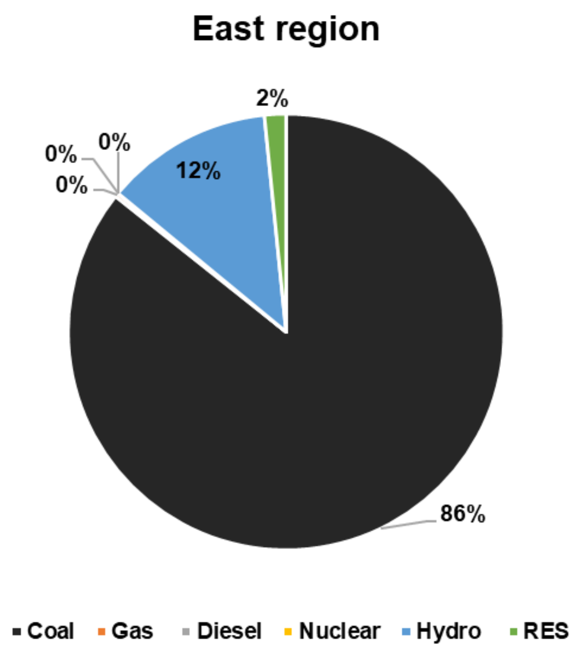


Figure (5) Power plant shares by technology in the East region [*Source: ATLANTIS_India, VISU*]

The power plant fleet in the ER is relatively old, since most of the dominant coal capacities were added subsequently in the late 1980s when cheap coal was mined in the region. However, as it is an export-oriented region, several ultra-Mega-Power projects (more than a GW of capacity) are planned in the region in the next few decades, which has to be looked in to, especially concerning the stranding of such large assets. Renewable energy expansion in the region has been neglected also because of the ease in availability of domestic and imported coal, and also the possibility of cheap natural gas imports from Bangladesh. No nuclear capacities exist or are planned for this region, and the focus of the regional energy regulation is more on the development of gas-fired capacities and large hydro capacities in the northern part of this region.

2.2.2. North Region

The North Region (NR) is the region with the highest capacity of hydro power plants installed, considering the geographical layout of the region [3]. Some of the largest dams (both head and capacity) are located in the region, closer to the Himalayan mountain range. Several hydro power plant projects planned in the northern part of this region have been delayed or cancelled, due to territorial disputes between India, China and Pakistan. The National capital city of New Delhi falls in the region. However, the population and the urbanization in the region has increased so quickly leading to the add up of coal- and gas-fired capacities. Along with the seasonal practices of crop burning in the region, this region hosts one of the most air-polluted areas in the world. Thus, significant efforts in the region are focused on the buildup of clean energy generation capacities. The existing 11 percent share of RES in the capacity mix is mainly from the small hydro power installations along with the several new solar PV and wind installations in the desert area west of the region. The GoI has mapped out the desert region for the strong promotion of solar PV and solar thermal technology installations in the area. Thus, a significant development of the RES share can be observed in the region in the coming decade. Two new units will be subsequently added to the existing regional nuclear capacity share. However, due to public disagreements, the project is still under planning stage, and a large delay in the execution of the proposed nuclear expansions is expected.

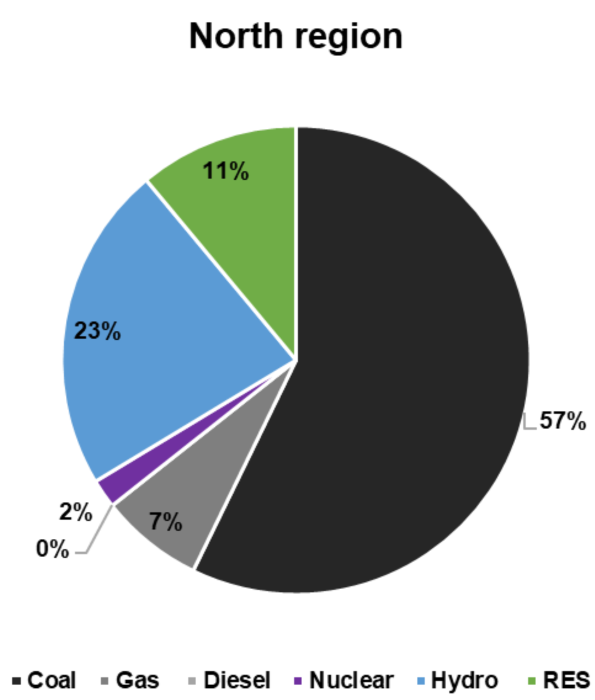


Figure (6) Power plant shares by technology in the North region [*Source: ATLANTIS_India, VISU*]

The energy policies on the development of the NR power plant fleet is somewhat unique. It is observed that after the year 2035, the national strategy excludes any addition of new hydro power capacities in the region, considering the plans for future Indian investments in Nepal and Bhutan. However, the several hydro power plants in the region are still only around fifty years old, which is usually smaller than half of the expected technical lifetime of hydro power plants. Almost all coal-fired capacities, except a few with lifetime extensions planned are expected to retire around the age of 45. The relatively older coal-fired fleet is expected to decrease considerably, in the next two decades. Thus, the electricity generated from ageing coal-fired capacities is expected to have significantly higher price than other technology types, making the coal-fired capacities in the region not so favorable.

2.2.3. North East Region

The North East (NE) region is unique in its own right, as there are major changes to be expected in the region. The NE region had a delay in urbanization and industrialization in comparison with the rest of the country, and thus were in a situation where all electricity needs (household) were met by small decentralized gas-fired and oil-fired power plants [26]. The availability of cheap natural gas from Bangladesh made natural gas the best and the least expensive source of electricity in the region. However, since the beginning of this decade, hydro- and coal power in the region has started to gain much attention, since the region is now a hub for tea, jute and other energy intensive industries. Initially, the development of a few hydro power capacities with the help of the central government seemed to be the best course of action, until the water sharing and the territorial disputes not only between the states of the region, and also between India, China and Bangladesh arose [27]. Thus, several hydro power plants now have a 'deferred' status in the capacity roster, which would mean that once the dispute is cleared, the construction of the plant could be immediately resumed. With regard to its unused hydro potential, the North East region in India has been dubbed the 'Power Cradle' of India. Considering this untapped hydro potential, which is the highest when compared to all other power regions, the GoI has been pushing to find a solution for each dispute around most of the larger 'deferred' hydro power stations and commission them as soon as possible, in lieu of the country's goal for reduction in carbon intensity of electricity generation.

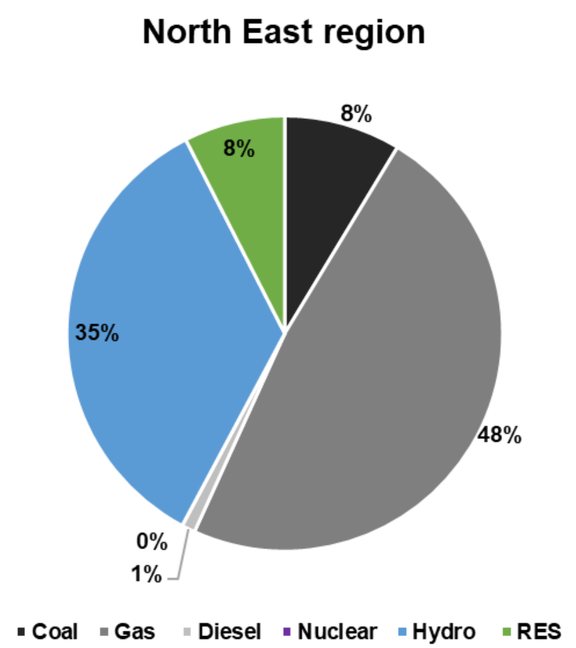


Figure (7) Power plant shares by technology in the North East region [*Source: ATLANTIS_India, VISU*]

It can be observed from the Figure (7) that hydro power in the region occupies a large share of the installed capacity mix, only next to decentralized gas-fired capacities. The seemingly large 8 percent of RES is from the several small hydro power capacities in the region, along with a small share of Solar PV. It is also observed that most of the power plants, especially the oil-fired and gas-fired plants are significantly old (> 35 years). However, even at the end of the simulation target year 2050, a significantly large share of hydro power plants is expected to still be operational for fifty to sixty years more. The largest of the hydro power plant capacity planned in the region is at the moment under construction, expected to be operational by the year 2021. A lot of changes in the region's power plant portfolio is expected, especially in the next decade.

2.2.4. South Region

The South Region (SR) of the country is characterized by the largest share of renewable energy, both wind and solar PV, and also the largest installed capacity of nuclear energy in the country. The region is already heavily industrialized and urbanized, that even with such a large available generation capacity, is still an import region and imports large shares of electricity from the coal intensive eastern region. The region also hosts two small hilly regions called 'Ghats' both to the east and to the west, with many small rivers originating making it a suitable location for small hydro power installations. Most of the recently proposed small hydro capacities, would add to the large RES share seen in the Figure (8). The early wind power capacities in the country were installed in the natural wind corridor region in the central part of SR, in between the hilly areas. Recent water sharing disputes between the regional states in lieu of draught in the summer season severely halts the development of the large hydro share in the region. The climate of this region is completely tropical, hence two seasons, dry/ summer and wet/rainy define the RES generation factors.

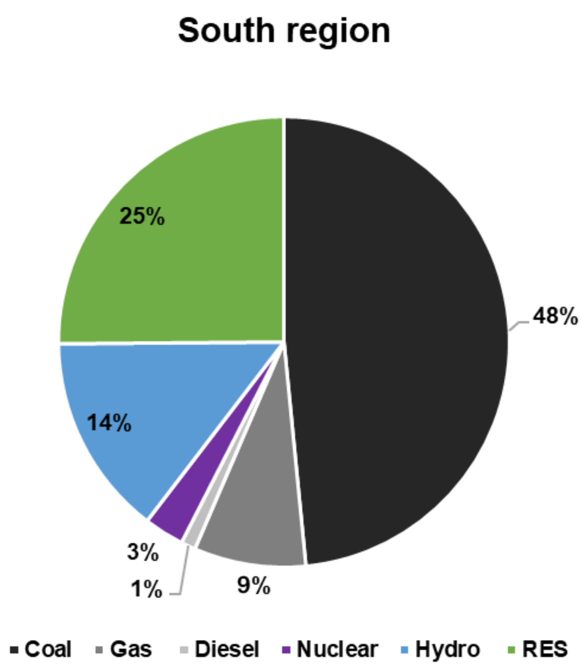


Figure (8) Power plant shares by technology in the South region [*Source: ATLANTIS_India, VISU*]

At the end of the simulation target year 2050, most of the already older coal-fired capacities, which are owned by the private sector are expected to go off grid, at the end of their technical life times. Several plans for nuclear expansion in the SR have been planned, especially when the new HT-FBR thorium reactor units successfully complete the testing phase. A lot of support in regards to small hydro power and RE has been proposed in this region. With large shares of capacity extensions planned, a large share of solar PV and wind capacities are expected to be still operational by the end of the year 2050 even without refurbishment of the planned and installed capacities. Roof top solar PV is gaining momentum, and most of the large industrial infrastructure in the region are to compulsorily install the unused rooftops for solar PV installations. Furthermore, lucrative subsidies offered in the SR both by the central and the state governments for repowering and extensions of the RES capacities point in the direction of RES, Nuclear and Hydro dominated capacity mix in the next few decades.

2.2.5. West Region

The West region (WR) of the country is well known for hosting the largest metropolitan Indian city in terms of both population and size, Mumbai. The development and urbanization of Mumbai started with the immense industrialization of the region around the city, hence the large share of coal-fired capacities can be understood. Also, Gujrat, the hub of manufacturing in India at the moment, also has several new capacity additions of privately-owned large capacities of coal-fired and gas-fired plants. The only offshore oil and gas field owned by the country is to the west of the region, in the Arabian sea, and the region has access to cheap domestically produced natural gas and oil [28]. Hence you can also see a larger share of gas-fired and oil-fired generating stations, located especially near the refineries on the western shore. The solar PV development in the region can also be accounted to its geographical location, as to the north west of the region there are waste lands and desert lands with dry climate and clear skies. The full load hours for a typical solar PV power plant in this area could roughly reach 2500 hours, so it becomes immensely effective and profitable to plan Utility-scale PV expansions in the region. Thus, solar PV forms a large share of the 14 percent RES share observed from the installed capacity mix.

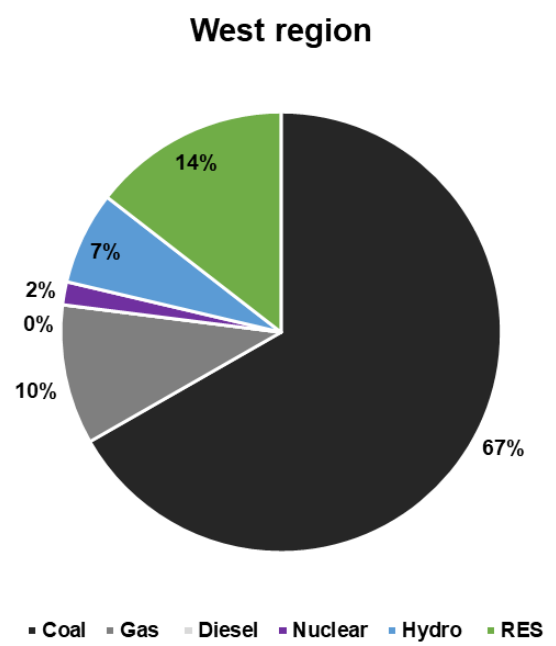


Figure (9) Power plant shares by technology in the West region [*Source: ATLANTIS_India, VISU*]

Without the refurbishment and lifetime extensions of power plants, majority of the coal-fired and gas-fired power plants in the region are expected to be at the end of their operational lifetimes by the year 2050. The region also has a high potential for installations of pumped storage power plants, at the mountainous region to the north. A major share of the existing hydro capacity in the region is relatively young (< 30 years), which makes the further investment in hydro power even more interesting. The first nuclear power plant in the country was mostly built in this region for scientific research rather than the power generation. However, subsequent unit additions were built for the sole purpose of generating power. This explains the large difference in the ages of the nuclear capacities observed in the power plant age structure.

2.3. Challenges faced by the Indian Electricity Sector

Based on several studies on electricity economics in India [9][12][15][21][29][33], several areas have been identified which could prove challenging for the GoI, in the process of the transformation of the country's electricity sector. With ambitious goals for increasing its VRE penetration in the power plant portfolio, India should first develop solutions to the already existing challenges within the electricity sector. Expansion of VRE capacity in the country without a proper strategy and solutions to the discussed challenges could prove to have severe repercussions on the energy system of the country. A brief discussion on such areas of interest has been provided in the following section.

2.3.1. Exponentially increasing demand and 'Base-load' mindset of regulators

With the increase of population in mind, it is not so unexpected that a country's electricity demand increases year after year, especially more so with an economically developing country like India. In the case of India, because of several rigorous economic reforms from the year 1991 with a large focus on the manufacturing sector [16], there has been an exponential increase in the annual growth rate of the electricity demand in the country. The country's Industrial demand sectors can be regarded as the main culprit for the exponentially increasing annual growth rate in electrical demand. The Industrial development in India was closely concerned with the manufacture, processing of raw materials and finished products, which are usually highly energy intensive. Also, the infrastructure boom created by the economic development led to an unimaginable expansion of urban areas resulting in a huge increase in the share of cement and steel industries: Cement, Steel and Aluminum industries are usually regarded as the most energy- intensive industries by several energy related publishing organizations like IEA, EIA and ExxonMobil.

The annual growth rate of electricity demand in India was at a steady rate of 2 percent every year from 1991-2000, and a 4.3 percent from 2000- 2006 and a steep rate of 6.9 percent from the year 2006 until the year 2015 [7][5]. Such a steep increase in the annual growth rate would result in several risky consequences in the coming future for the country. Also, with the energy use and economic development strongly coupled, such a situation always prioritizes the base load mentality, which will further encourage the addition of the cheapest power plant capacity- Coal. Therefore, it is this 'base load' mentality of energy regulators in the country that has to be examined.

Base load fundamentally means the load which can be expected throughout the 24 hours in a day, throughout the year. This would mean that the minimum most electricity demand to be covered, in the country over a year would form the base load. In a country with almost 30 million people (~ 1 percent) without access to electricity in 2018 [5], only base load satisfaction is given the utmost importance, next to only its economic development. India is even now predominantly focused on building such 'base load' power plants, to secure its minimum electricity requirements. It seems pretty reasonable that policy-makers in India usually have a lot of focus on 'base load' power, as the country's need for a source of 'reliable' power that is available throughout the year is uniquely high. With this special need to ensure sufficient energy supply, an almost continuous addition of coal-fired capacities has been observed in the country, with every consecutive year [12] [16]. An illustration of the electrical load variation in the year 2011, and the corresponding load duration curve is as shown in the accompanying Figure (10), where the base load is highlighted.

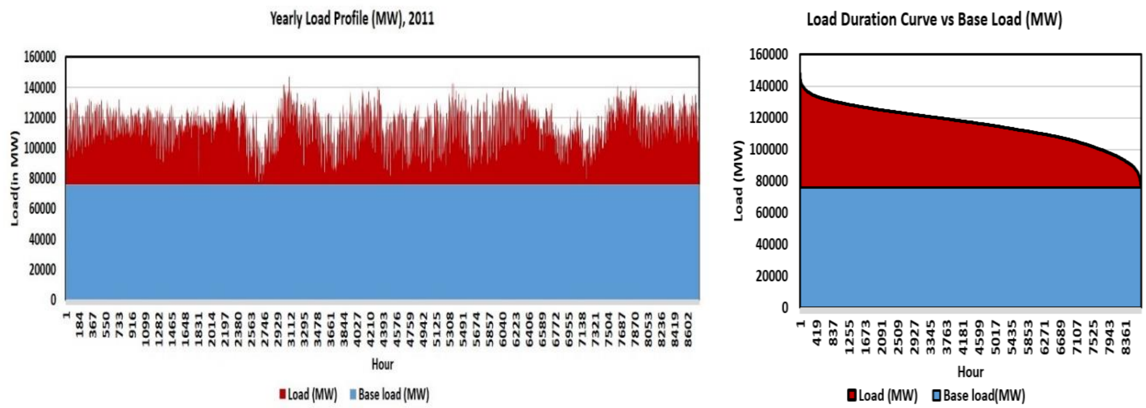


Figure (10) Electrical load profile in India for the year 2011 [*Source: CERC, MoP, India 2011*]

It can be observed that the electrical load in India has no such predominant seasonal variations throughout the year, the base load roughly accounting for around 52 percent of the yearly peak. This would mean that the base load constitutes for more than half of the total annual electricity demand. The intermediate and the peak loads are usually shared mostly by commercial and domestic sectors, while the industrial sector which usually involve continuously operated processes, majorly occupy the base load region. It can also be observed here that the base load is mainly a characteristic of electricity demand, rather than a necessity of the supply side [19].

The base load in India is traditionally covered by the so-called ‘base load’ power plants such as coal-fired or nuclear power plants which have higher availability factors and a steadier power output than many other power plant technologies. Such power plants are usually characterized by high capital costs and comparatively lower variable costs than other flexible generation technologies. The intermediate load is usually covered by Combined Cycle Gas Turbine (CCGT) and gas-fired plants, and the peak loads by gas-fired and oil-fired power plants. It is generally accepted that these ‘peak load’ power plants have lower capital costs, but comparably very high variable costs. By the end of the year 2016, India had an installed capacity of 186 GW of coal and 5.78 GW of nuclear thermal power plants. Also, a capacity of 24.5 GW gas and 994 MW of oil thermal power plants is expected to cover the intermediate and peak loads [3]. Recent developments in the energy sector have shown a significant growth in the renewable energy, accounting up to 40 GW (excluding hydro power) of installed capacity. The added renewable capacity constitutes of mainly on-shore wind and solar PV capacities, and a small portion of biomass. A Figure (11) illustrates the fluctuating nature of the VRE technology, with a comparison of the average load, wind and solar PV temporal variations over a year.

For now, even with smaller flexibilities, the role of the ‘base load’ power plants is significantly large, due to their constant output. But with a higher share of renewable energy in the future, the Indian electricity system would require a higher level of flexibility [30] between its components. Thus, it cannot be completely guaranteed that any technology will run at a high utilization rate or even provide a constant output. Subsequently, the significant role of such base load power plants is more likely expected to decrease. Additionally, as electrical load is inherently variable, the fact that a heterogeneous mix of different generation technologies, by bringing in different degrees of variable costs would be a sensible option, and also be more cost effective with higher flexibility in output.

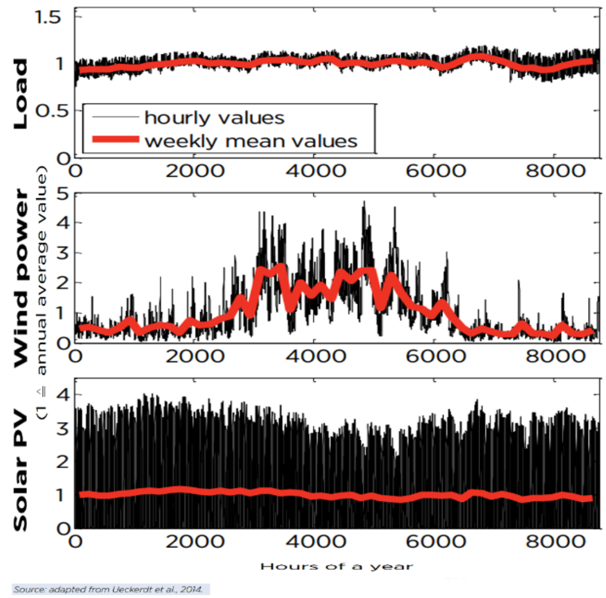


Figure (11) Comparison of average electrical load, wind and solar PV temporal variations in India 8*Source: Ueckerdt et al, 2014*]

2.3.2. Dependency on coal-fired technologies and energy-related emissions

India's electrical transformation requires a bigger push than most of the other electrical economies, due to its unique dependency on its coal-fired power plant fleet. As discussed, after the economic reforms of 1990, India put major priority on the manufacturing sector spurring the economy to improve, thereby creating a large industrial demand. This led to the unchecked continuous addition of coal-fired capacities with cheap generation costs. For a long time until even now, as mentioned previously, the Indian electricity system prioritizes base load coverage, which covers up to 52 percent of the yearly peak.

To sustain the economic development, the manufacturing sector grew larger every year, and without a sustainable strategy, the coal power plant fleet also started to grow at an unimaginable pace. Initially, most of the coal used in the power sector was cheap coal mined internally, but eventually, as the coal-fired power plant technology started improving, India started observing a large import in the high-grade overseas coal. With time, an unbreakable dependency of the Indian economy on coal imports was established.

Once India agreed to curtail the country's energy related emissions by 30 percent of its 2000 values by the year 2030 [1], and the SDG 2030 [35] to promote access and infrastructure to clean energy, the significant challenge of the dependency on coal power was identified as a challenge by many experts. With subsequent addition of VRE capacities like solar PV and wind power, the country now needs the coal-fired plants to stabilize the electricity generation, along with effective base load coverage. To eventually lose this dependency on coal-fired generation, a good strategy involving the use of several other possible technology shares, i.e., a diversification of power plant fleet has to be planned.

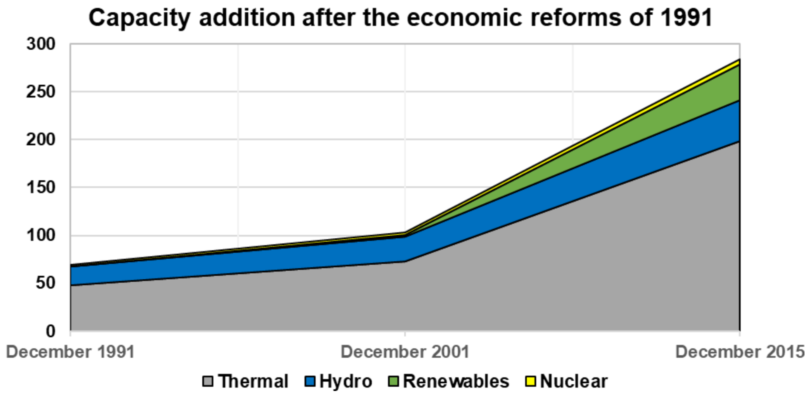


Figure (12) Comparison over the years of the installed capacities in the Indian electricity sector [*Source: CEA*]

With the global climate change being one of the major priorities of most of all the countries in the world [6], the carbon footprint of India will play a major role as it houses almost 17 percent of the population of the world. India has some of the most air-polluted cities in the world, New Delhi topping the list followed by Mumbai and Bangalore [31]. To curb the pollution issue on a city-level, the state government of Delhi had to shut down a coal fired power plant, implement traffic regulations of restricting the use of vehicles in the city of New Delhi. Thus, the pollution levels and energy related emissions have become a major source of concern to the country.

With the annual electricity consumption of India ranked the third highest in the world (d), the electricity sector of India can have major impacts on a global scenario. Also, with the large coal dependency, the electricity generation sector becomes one of the major sources of energy related emissions in the country, and can thus have major impacts on the global emissions scenario. The GoI has argued, for several years, that 'developed' countries like the UK and the USA have spent almost a century industrializing their economies without any emission restrictions, and therefore debated that developing countries should have the opportunity to do the same. However, India is determined and committed to reduce its carbon intensity according to the Intended Nationally Determined Contribution (INDC) plan (e)(f). The resolve to improve India's reputation in the battle against climate change has led the GoI to seriously explore strategies and approaches to decouple its economic development from energy related carbon emissions. The Figure (13) describes the proposed projections for the reduction of carbon intensity in India.

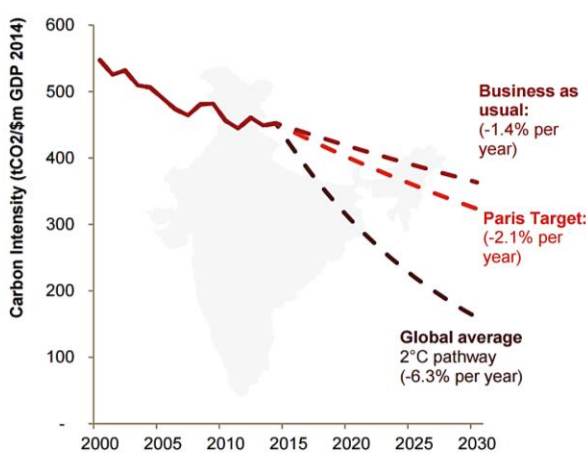


Figure (13) Business as usual and the projected carbon intensity reductions in India [*Source: PwC*]

India's energy related emissions grew at a rate of 8.2 percent in the year 2014, driven by a double- digit demand growth in demand for coal, as power consumption increased in line with the rapid GDP growth of 7.4 percent [13][16]. With new initiatives focusing on promoting the manufacture of goods in the country, the contribution of the industry sector to emissions is also expected to be dramatically huge.

Overall, on a longer period, India has reduced its carbon intensity by 1.4 percent per year, between the year 2000 and 2014, which is slightly higher than the global average of 1.3 percent per year [31]. Although the share of renewable share in the country's energy mix remained at a constant of 7 percent, there is a high growth in coal-fired power generation to keep up with the electricity demand. The reduction in the carbon intensity in the country falls short of its targeted 2.1 percent yearly reduction by 2030.

2.3.3. Transmission and distribution efficiency

The transmission and distribution networks connect various generating capacities across the country to its various demand centers. India has a vast network of transmission lines covering almost 126965 circuit kms [32]. 'One Nation-One Grid- One Frequency' (g), an initiative by the GoI and MoP, ensures the coupling of different regions and that all the regional networks have a strong interconnection, operating at a single frequency. HVDC technology was implemented for long distance transmission access, to effectively connect the heavy demand centers to big power plants.

However, the efficiency of the distribution networks managed by the state-owned distribution companies (DisCom) has been severely low, thus resulting in large financial and energy losses. In 2013, India's Transmission and Distribution (T&D) losses accounted to almost 23 percent, and the Aggregate Technical and Commercial losses (AT&C) almost 25.4 percent, though much lower than previous years, is a major problem [3][32]. In simple terms, this loss rate would mean that the electricity generators would have to generate up to five units of electricity for every four units they sell to their retail and industrial customers. A loss of such magnitude could only mean a financial suicide, particularly when coupled with already subsidized electricity retail prices [33]. The MoP has outlined a 50 billion US $ investment program to upgrade the capacity and efficiency of the Indian electricity transmission and distribution grid. Also, incentives to upgrade the capacity of HVDC lines in the network for interregional interconnections are also provided, to improve the flexibility and security of supply. The Figure (14) explains the overall decrease in T&D and AT&C losses through the years, representing the improvement in the transmission grid.

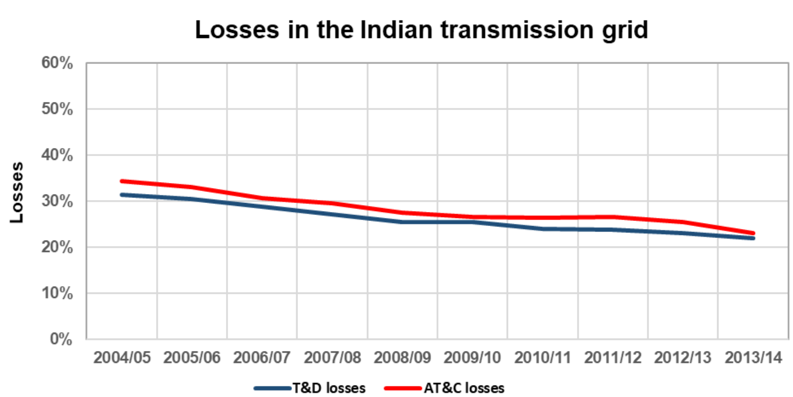


Figure (14) T&D losses and AT&C losses in the Indian grid (2005-2014), [*Source: CEA, MoP*]

The consideration of whether to have complete reliance on central generation or not has become more important. When possible, a small portion of the massive investments in large scale generation plants planned by the administration might be better directed to increasing transmission capacity, especially using multi-link HVDC technology, placing a much higher reliance on distributed generation, and optimizing the network as it now exists [32][33]. Many of the prosperous economic zones in India like Mumbai, are prosperous simply because they have their own generation sources installed, shielding them from the poor reliability of the public network. Thus, distributed generation can add considerably to balancing load imbalances across the various grids and act as an effective supply (when aggregated) during peak periods.

Meeting each of India's energy challenges by large scale renewable integration, depends also on improving the efficiency of the transmission and distribution grids. In other words, a significant loss in transmission and distribution could only cause major problems in meeting the on-grid consumer demand, even with the availability of centrally generated power.

2.3.4. Financial situation and renewable penetration

The GoI is faced with a challenge of limited budget and several development projects in different sector. The power sector in India can be described to be 'Drowning in debt'[33]. Three of the leading private power companies in India needed refinancing due to the losses incurred. For example, a nationalized Bank in India had to refinance a notable power plant company and extend the loan repayment period to 19 years instead of 10 years under the 5/25 scheme of the Reserve Bank of India (h). The weak financial footing of the industry has left the Indian domestic banking sector an estimated loan of 100 Billion US $ to just 10 of the larger power and infrastructure groups. This situation could pose major setbacks to the ambitions of the GoI to increase the renewable share in the coming decade. With almost zero marginal cost of production, the renewable energy technology could work immediately to undermine the viability of coal-fired power plants that usually have high marginal costs.

Furthermore, the MoP's plan to gain access to the global debt capital markets, the cost of renewables in India could be expected to lower significantly. As the technology of renewable energy develops rapidly, many coal- fired thermal power plants will definitely prove to be stranded assets, unable to generate any financial return. India may most likely encounter a similar electricity sector problem as Europe in the past decade with major utilities like E.ON and RWE seeing unprecedented shareholder wealth destruction [33].

With India also in agreement with the United Nations for the SDG 2030, especially the goals 7, 8 and 9, which ensure access to clean and safe energy, improvement of the overall economy and development of sustainable infrastructure [35] respectively, the administration of the country has now to plan its financial decisions in a much more strategic way, especially concerning its power sector.

2.3.5. High penetration of Variable Renewable Energy and resulting 'Integration' costs

Though India's interest in large scale renewable energy integration developed mainly in the last decade, the GoI has ambitious plans in this sector. After the motivation from the global energy community for energy transition in India, the GoI revised its plans to increase its solar capacity fivefold from its initial target of 20 GW to an optimistic target of 100 GW by the year 2025. 75 GW of wind power has also been planned to reach its overall renewable targets of 175 GW by 2025. Currently, around 7 percent of the total electricity produced is from renewables. Wind energy in India is already considered competitive, as the LCoEg from wind power was almost same or less than that from the fossil fuel. However, the LCoEg from solar power was 11.79 percent higher than imported coal in 2015 [24] [36]. The cost is expected to decrease over time due to technological learning effects that drive the solar prices down while fossil fuels become comparatively more expensive. Solar power is projected to be cheaper than imported coal-based power in 2019. The Figure (15) shows the calculated forecast for LCoEg from imported coal, solar energy and wind energy in India.

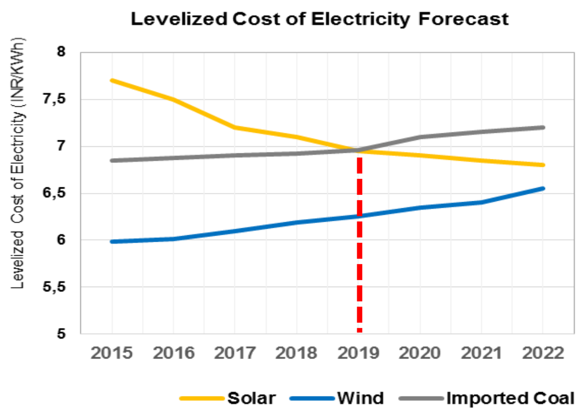


Figure (15) Levelized Cost of Electricity generation from coal, wind and Solar PV in India [*Source: MNRE, Shrimali et.al*]

A large-scale integration of VRE power plants also inflicts specific integration costs at the system level [19]. These integration costs are just additional costs on the power system, due to the integration of such power plants with uncertain and less predictable generation. Normally, VRE integration costs are low or even sometimes negative, when their share in the system is low [30][37]. This could mean that the integration would save costs on a system level. With higher shares of VRE integration, the concerned challenges and technical obstacles due to fluctuation tend to decrease, but the integration costs are expected to increase. Due to the temporal variability of such sources, they cannot be relied upon during the peak load times. Thus, a considerable scale of renewable capacity would also need a considerable share of back up technologies like energy storage, and back-up conventional power plants.

Unfortunately, modular LES options like battery technology and hydrogen storage are currently highly expensive, and options like Pumped Hydro capacities have both high geographical, territorial dependencies and are highly capital intensive. This makes the overall integration of the VRE capacities less financially effective. The geographical dependency of VRE sources also create a need for investments in transmission and distribution networks, which also needs a lot of initial capital.

The level of integration costs of VRE is usually highly dependent on the characteristics of the power system involved. Thus, a solution for such an integration problem would be to make the Indian power sector to ‘VRE friendly’ by investing in flexible generation plants, strengthening the grid and flexible demand i.e., Demand Side Management (DSM). Also, the introduction of regulatory frameworks and innovative grid operation protocols could significantly reduce the integration costs by harnessing the available potential for technical flexibility. To effectively reduce the system integration costs, it is necessary to shift from capital intensive base load power plants like coal power plants, to intermediate and peak load plants with higher flexibility and lower capital costs to complement the high VRE shares.

2.3.6. Energy usage efficiency

The GoI and the MoP have already identified energy efficiency as one of the key factors deciding the country's sustainable energy future. Efficiency of electricity use can bring about considerable reductions in electricity demand, and in turn, energy related carbon emissions. In a country like India with a high rate of demand growth, energy efficiency should prove to be a major benefit. The GoI has undertaken a bi-directional approach to meet the electricity demand while ensuring minimum growth in CO_2 emissions i.e., on the generation side, promotion of renewable energy in the electricity mix mainly through solar and wind power. On the demand side, efforts are being made to efficiently use the energy through various innovative policies under the Energy Conservation Act 2001 (i).

A variety of measures have been introduced by the BEE [10], some of them include the usage of efficiency standards and 'labeling', specific codes for building constructions, DSM schemes, and energy efficiency standards at the several industry levels. Some of the largest efficiency standards are defined for the energy intensive industries in India, especially metal works and cement industry. The efficiency and savings directive had an encouraging response from citizens and the industries, as energy savings mean lesser expenses on electricity. The GoI has also introduced efficiency standards for street lights, traffic lights, water pumping and also taken the initiative to distribute LED bulbs to replace the non-efficient incandescent bulbs, throughout the rural areas in the country.

The Figure (16) shows the progress of electrical energy savings in terms of avoided capacity each year by participating units. Several steps to educate children about efficient electricity usage through different educational schemes and competitions have been undertaken by the GoI (j). A large emphasis on energy efficiency with regards to electrical demand development has been given in the study conducted in this doctoral thesis.

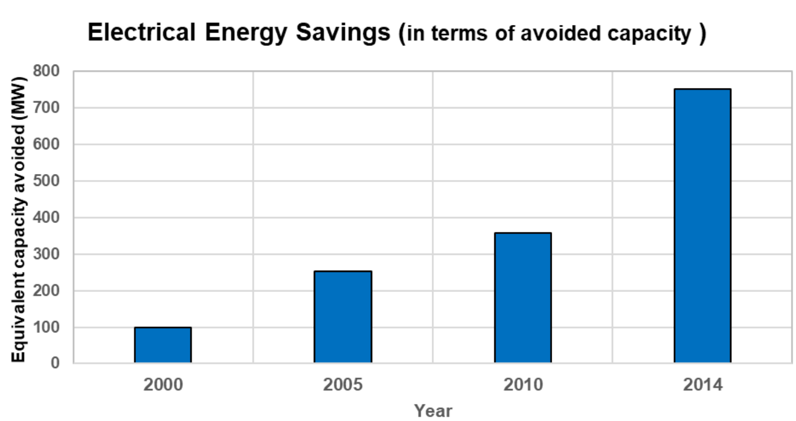


Figure (16) Electrical energy savings per year in terms of equivalent avoided capacity (MW) through the implementation of energy savings process in India [*Source: BEE, MoP, GoI*]

2.3.7. Additional demand from E-mobility

Transportation, along with the electricity sector, is the other major source for energy-related emissions in India. With the population of the country increasing at an alarming rate, and the ownership of vehicles in turn on the increase, major cities already face problems with air quality. Thirteen cities, out of a list of twenty most polluted cities in the world, are in India [31]. The regional state governments, responsible for these cities are now forced to take actions regarding the vehicular traffic. Eventually, the regional problem has now escalated to a national level. Thus, the transportation sector has been included in to the National Action Plan for Climate Change (NAPCC) (f), which plans strategies for the reduction of India's carbon foot-print in the next few decades. With what started as a social trend in the early 2000s, Electric Vehicles (EV) are now expected to play a major role in the country's sustainable future.

Thus, several preliminary plans and visions for electromobility (e-mobility) are already sketched out, and mostly will be implemented in newly urbanized areas as pilot-projects. The GoI, along with the planning commission of India, have already published an initial road map till 2020 along with the support of the National Electric Mobility Mission (NEMMP) (k). Development areas have already been identified and specific investments in research and development have been made. The GoI has made several market surveys and has estimated that by the year 2020, a range of 6-7 million units in new vehicle sales as the market potential. This is projected to include 3.5 -5 million pure electric two-wheelers (BEVs), 1.3-1.4 million Hybrid EVs and 0.2 - 0.4 million other pure EVs (4W, buses, LCVs). The Figure (17) depicts below the projections of the different EVs on road till the year 2030, according to the recent Indian EV strategy. The major challenge to India concerning an e-mobility transition is the T&D losses in the transmission grid. Several studies in the UK [38] showed that with uncontrolled charging, there was at least a 2 percent increase in the peak power demand with 10 percent Plug-in Hybrid EVs (PHEV).

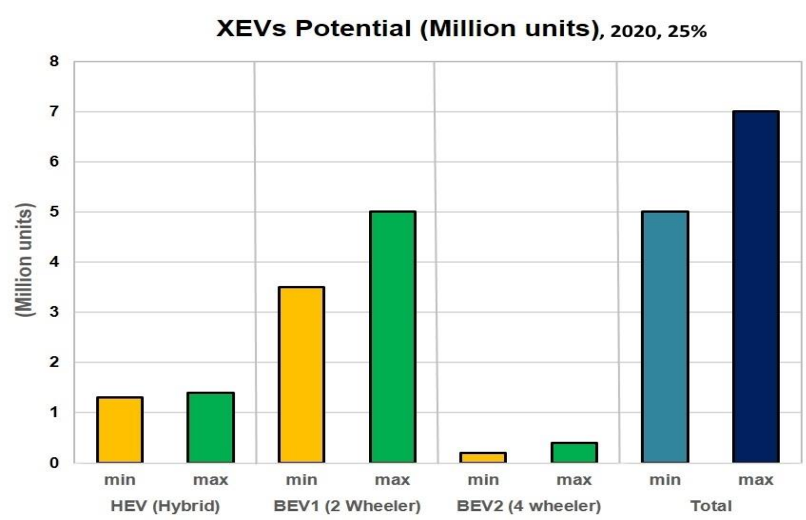


Figure (17) Projections of EV potential in the market, [*Source: NEMMP, India*]

With India already experiencing an energy crunch (demand-supply gap), the grid losses add up to the problem and become a major issue. However, one of the major advantages for the country concerning e-mobility infrastructure is that around half the country is said to be yet urbanized, including the transmission infrastructure in several regions [39]. The present case of most urban areas and cities in India, it is notable that the new infrastructure has to be intelligently integrated or upgraded with already existing infrastructure. To support the NEMMP, several support schemes like Faster Adoption and Manufacturing of Electric and Hybrid vehicles in India (FAME India) for faster adoption of green vehicles, and Technology Platform for Electric Mobility (TPEM) for research on component manufacture have been additionally implemented. However, the GoI have yet to provide a long-term plan regarding the e-mobility goals (k).

The introduction of e-mobility, to decrease the contribution of the transport sector on the emissions of the country, could also prove more fatal, rather than beneficial to the overall electricity system in its current state. Over the long run e-mobility may dampen the influence of primary energy intensity of the country, but for the country to manage its current economic development, energy transition and the transport sector transformation together would be an immensely impossible task. Furthermore, the management of the variable demand resulting from charging strategies could also be an extra complexity in the already challenge riddled T&D sector. Even with India's ambitious target of solar PV and Wind energy expansions by the year 2025, it would still need a further larger share of added conventional capacity to manage the additional demand from e-mobility. However, an analysis [40] on the additional load created by both peak and off-peak charging strategies were analyzed, both for a centralized and a de-centralized plan. It was found that depending on the region, a 2.3 percent to 15 percent increase in peak electrical load was observed, and a significant reduction in CO_2 emissions was observed for an off-peak charging strategy and 25 percent EV penetration for the year 2040.

2.4. Temporary measures to address the challenges faced by the Indian electricity sector

A temporary measure is usually not the best solution to any problem, rather a solution only to manage the present situation. The GoI realizes the importance of finding a sustainable solution to the challenges blocking the transition of the Indian electricity sector into emission free energy. However, finding a sustainable solution and its implementation could take much longer than the amount of time India has to fulfil its obligations to the global community. Thus, the GoI has shown interest in some temporary solutions, which could tackle the challenges of continued electricity access and emissions restrictions both together, which are discussed in the following section.

2.4.1. 'Clean' coal technologies

With the recent reforms in regulations and improvements in the domestic coal mining, coal easily still undoubtedly remains the cheapest source of conventional power [41]. Though India is committed to decrease its energy related emissions by 2030, and the VRE installed capacities have considerably increased, coal still retains a significant share in the electricity generation mix. Efforts are being made by the GoI to promote and increase the use of 'clean coal' technology, as outlined by the NAPCC in 2008 [42]. The Indian electricity promotes the use of CCS, Super critical boilers and CC technologies in all the proposed coal-fired installations in all the power regions. The NAPCC recommends that, in the immediate future, in view of the major coal -fired power generation in the next decade, 'Super Critical' boilers are to be used, and the introduction of 'Ultra-supercritical' boiler technology, when the commercial viability of such technologies is verified. The ultra-supercritical boiler technology flashes the steam by reaching temperatures and pressures above the critical point of water, thus reducing a considerable energy input in the overall power cycle. This would mean a much lower quantity of coal to produce the required amount of electrical energy, meaning lesser coal consumed and smaller emissions.

The 'clean coal' technology however, implements the use of several filters and catalysts to subsequently clean the emissions from a coal power plant (CCS), also while providing a higher conversion efficiency. The implementation of new capacities of 'clean' coal technologies have been considered in the scenario Business As Usual (BAU) scenario, later defined in the course of this thesis.

2.4.2. Combined Cycle Gas Turbine (CCGT) capacities

The Indian electricity sector always has relied on gas-fired capacities for flexibility options and covering of variable peak loads throughout the year. To ensure continuous electricity access, majority of large energy intensive industries find it both technologically and financially feasible to build their own gas-fired capacities than completely relying on centrally generated power. However, with regards to the NAPCC, regulations from the GoI puts a limit on the maximum capacity of gas-fired capacities these investing industries can build, preventing the unchecked addition of gas-fired capacities. This is in term with the GoI's plans of restricting energy related emissions and to be independent of varying prices for Natural gas in the region. Additionally, the gas-fired capacities also provide balancing options due to their high flexibility in generation of electrical power, inherently decreasing the integration costs due to higher shares of VRE penetration.

Furthermore, the state of the art CCGT technologies can actually be highly efficient and less emission intensive than the current gas-fired technologies, thus making it a viable temporary solution to fill up the generation gaps in the capacity mix. The GoI plans to stop refurbishment and renovation of coal-fired and gas-fired power plants at the end of their lifetimes, and replace them with subsequently lower capacities (as required) of CCGT expansions. These CCGT extensions are planned to provide flexibility options to the electricity system, mainly at demand centres, rather than cover electrical load at all times. This temporary measure has also been undertaken in the scenarios defined in this thesis.

2.4.3. Nuclear capacity advancements

India has always had the ambition to use nuclear energy for the electricity generation on a large scale as early as the 1950s [43]. However, due to India's disagreement of the Non-Proliferation Treaty (NPT) (l) for use of nuclear technologies, the growth of nuclear power in India has been enormously stunted. India is also a nuclear weapons state, which means that the international community considers it severely risky to include India in any of the regular nuclear trade, both fuel and technology. The acquirement of nuclear reactor technology has been a major obstacle in the development of nuclear energy for peaceful use in the country.

On the contrary, the first nuclear reactor in India (also in Asia) was established in the year 1957 (m), and was a pool-type reactor, supported by Uranium fuel provided by the UK on agreement to promote the use of nuclear technology for peaceful purposes. Since then, several attempts have been made by India to increase their share of nuclear power in the country in a gradual manner. The most recent development is the development of a High-Temperature Fast Breeder Thorium Reactor (HT-FBR) (n), in cooperation with Russia to use the abundant source of Thorium in the country's coasts [44]. A test reactor is already in operation, and another one is planned to be built and commissioned after the testing phase. This new reactor is believed to be much safer than the normal fast breeder reactor with very high safety standards, and is said to generate less nuclear toxic waste at the end of each fuel cycle (n).

Nuclear power in India has not just faced opposition in the global scenario, there has been severe opposition by the local communities, after the Fukushima disaster of 2010 in Japan. Though stunted, India plans to increase its nuclear capacity to almost 10 GW to be able to generate 12 percent of the overall load in the country by the year 2020. This goal was developed in order to discourage the use of coal-fired conventional technology for electricity generation in India, and to also to fulfill the COP21 goals regarding carbon intensity of energy in India [31][43].

The second major reason for the stunted growth of nuclear power in the country is the acquirement of nuclear fuel. Regarding the trade of nuclear fuel with the international community, India cannot participate in nuclear trade due to non-agreement of the non-proliferation treaty and also due to the inability to be a part of the Nuclear Suppliers Group (NSG) (o) after consistent failed attempts. The GoI has made clear statements that it will not cease its future attempts, to participate in the international nuclear market. Furthermore, large deposits of uranium have been recently found in the southern region of the country. One of the biggest natural uranium deposits were found in the central-east region of the country in the year 2014, though the lack of enrichment technology forces India to depend on treaties with other nonproliferation countries like Iran for the refinement of the nuclear fuel. With the advent of the thorium reactor, the refinement of the thorium fuel can be done on the nuclear reactor site, making things easier for the country's nuclear ambitions. The country's uranium and thorium deposits are distributed in the south-eastern part of the country as shown in the following Figure (18)

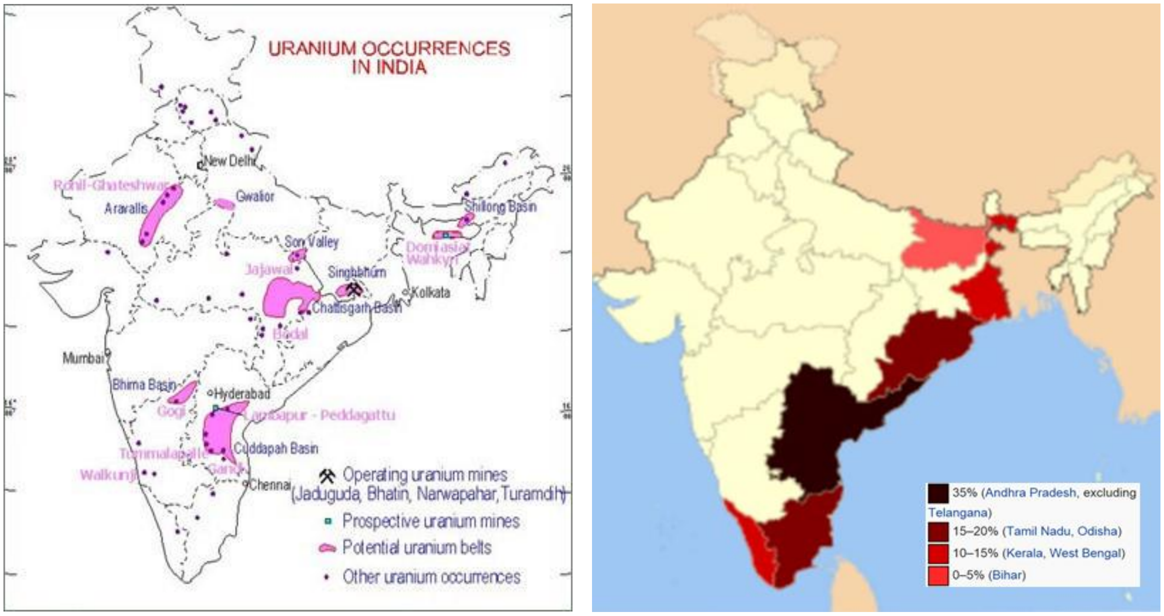


Figure (18) India's identified Uranium (left) and Thorium (right) deposits, [*Source: pmfias*]

Several of the nuclear power plants cumulatively forming around 6 GW of the country's power plant mix are located overall in the South, West and the North power regions of the country. Plans for at least 2 GW of capacity is already on the drawing boards, and can be expected to be commissioned in the following decades. A map of the country with the available and planned nuclear power plant capacities are as shown in the accompanying Figure (19). In the country's five-year plans, nuclear energy always takes up a major part, which includes the planning, development, operation, maintenance and commissioning of existing and new nuclear reactor.

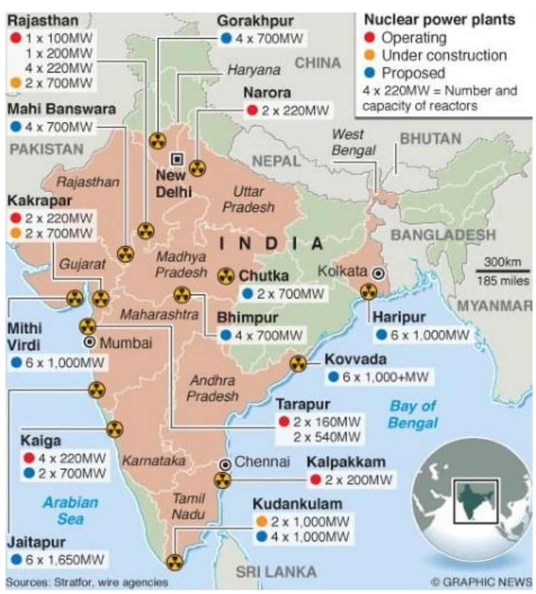


Figure (19) Illustration of available and planned nuclear capacities in India, [*Source: pmfias*]

In the scope of this thesis, the possibility for a nuclear utopia for India is indeed considered, as it can be one of the simplest ways to provide a solution to two of India's major challenges: Continued energy access and Energy related emissions. However, with regards to common sense, in the scope of this thesis, only the safest of the nuclear reactors are even thought of, i.e., the new units Thorium HT-FBR capacity is defined with a higher than usual capital cost, accommodating extra capital for the implementation of high safety standards seen in the European Pressurized Water Reactor (EPR) (p), which is one of the safest reactor technologies in existence today.

Several technological treaties have been signed by the Indian and the Russian governments to build nuclear power plants in Bangladesh and Sri Lanka. Russia has been commissioned to build a Boiling Water Reactor (BWR) power plant of 1000 MW capacity in Bangladesh (q), while India has been contracted with the task of building a BWR plant in Sri Lanka by the year 2025 (r). These nuclear power plants are expected to improve the energy situation in both countries, as Bangladesh heavily relies on natural gas and coal for power. Similarly, the use of oil for a large share of the electricity generation in Sri Lanka, the country faces immense challenges with the volatile nature of oil prices [45]. The nuclear power plants are also expected to cement the friendly ties of India with both the countries. Several cross-border lines between India and the two countries have been planned, to improve the quality of the electricity supply in the whole sub-continental region.

These measures have been implemented in this thesis in the form of a nuclear oriented scenario, where the nuclear capacity expansions planned in all the model regions in the Indian Sub-Continent have been included. However, it is to be noted that the use of nuclear power, with regards to the hazards involved, has been thoroughly discouraged. The analysis is only conducted for the sake of research and interest in exploring different strategies to solve the energy crisis in the sub-continent region.

2.4.4. Demand Side Management (DSM)

The GoI has now considered DSM as a viable option to manage the electrical demand in the country [46]. DSM to improve quality of service in the electricity sector is quite a new concept in the Indian electricity sector, as there has been an ever-existing but slowly narrowing demand-supply gap in the country. However, due to unavoidable requirement of covering the base industrial load, the traditional markets in India employed the DSM technique of load shedding quite early on, favoring the coverage of industrial load while severely compromising the coverage of the domestic electrical load. The TSO of the particular region would notify the domestic customers of a load-shedding schedule, carried out sometimes almost every day in the dry season, or during the yearly maintenance of the bigger thermal power plants in the region.

However, India will face yet another challenge of managing the electrical demand with a high penetration of VRE power in the electricity system – problem of over production during off peak periods. Thus, the MoP and the BEE have been rigorously working out DSM strategies for a scenario concerning over production by RES capacities in the future. The ease of carrying out DSM strategies in India is expected to be very high, as the end users rarely offer any displeasure to smaller changes in the electricity system when granted continuous access to electricity throughout the year.

The other possible way is the implementation of efficiency directives in energy intensive industries and households, thus ‘managing’ to saturate the increasing electricity demand in the region. The BEE has published a list of directives for the improvement of energy efficiency in India and the future plans regarding energy efficiency in the region. The electricity and power market in the country already have rolled out some peak shaving and load shifting measures by varying their electricity prices in peak and off-peak periods, especially for the industrial demand sector. The implementation of the energy efficiency directives has been conducted in all the scenarios discussed in the course of this thesis, thereby limiting the rapid increase of electrical demand in all the model regions by the year 2035.

2.5. Renewable energy potential in India

The Indian RE sector is considered to be the second most attractive renewable energy market in the world, the country already ranks fourth in the world in terms of total installed wind power capacity (s). The country added 11.79 GW of power generation capacity from RE sources between the months January and November in the year 2017. With the increased support of government and improved economics, the sector has become attractive from investors perspective. As India looks to meet its overall energy demand on its own, which is projected to reach 15.82 TWh by 2040, renewable energy is clearly set to play an important role.

The market size of the Indian RE sector is significantly large, when compared to many other developing countries. Along with the cooperation of around 150 countries, India played an important role in the founding of the International Solar Institute (t), with focus on the development of technology related to solar PV and components. As of the year 2017, the total installed renewable energy capacity in India reached 62.85 GW, which is around 18.8 percent of total energy capacity of the country (333.5 GW) [3].

The total installed wind power capacity in the renewables mix alone stood at 32.85 GW (52.27 percent), while the solar power installed capacity was at 17.05 GW (27.13 percent). The total installed solar capacity in India is expected to be 8 percent of global solar capacity by the year 2035 [23][35]. With an overall potential of 363 GW and with policies focused on the renewable energy sector, the northern region in India is expected to become the hub for renewable energy in India.

2.5.1. Solar Photo-Voltaic potential

Most of India's climate topology is termed to be tropical, meaning a large abundance of solar irradiance, almost throughout the year. Considering the vast potential of 784 GWp (with available area assumptions), as already discussed, solar energy can be a single solution to India's energy problems. The Figure (20) shows the solar potential in India, with the assumptions that only around 2 percent, 20 percent rooftop area and 3 percent of waste land area per state could be used. However, in reality, to meet India's energy and climate challenges, three very different sectors of solar energy deployment are needed- Utility-scale Solar, Distributed Solar and Off-grid solar [23][24].

The GoI has recognized the importance of all the three sectors of solar energy and have set individual targets for each of the sectors. The GoI's target for Utility scale solar PV of 60 GW by 2022 claims its highest priority. The Distributed solar PV (rooftop PV) target of 40 GW and Off- Grid Solar of 3 GW by 2022 are more concentrated on securing access to electricity to curb the demand- supply gap. The utility scale sector and distributed solar sector address the major energy challenges like the energy related emissions and the energy import dependency, while the Off-grid solar sector is aimed at rural electrification and improving energy access in the remote parts of the country.

The identified potential for generation from Solar PV is seen to be distributed almost evenly throughout the country, especially in the western and the northern part of the country. The Eastern and the North Eastern power regions seemingly have lesser potential in comparison, but smaller installations, particularly to contribute to the off grid solar strategy can be implemented. Thus, the large motivation of the GoI can be explained with the availability of such a large and distributed resource potential.

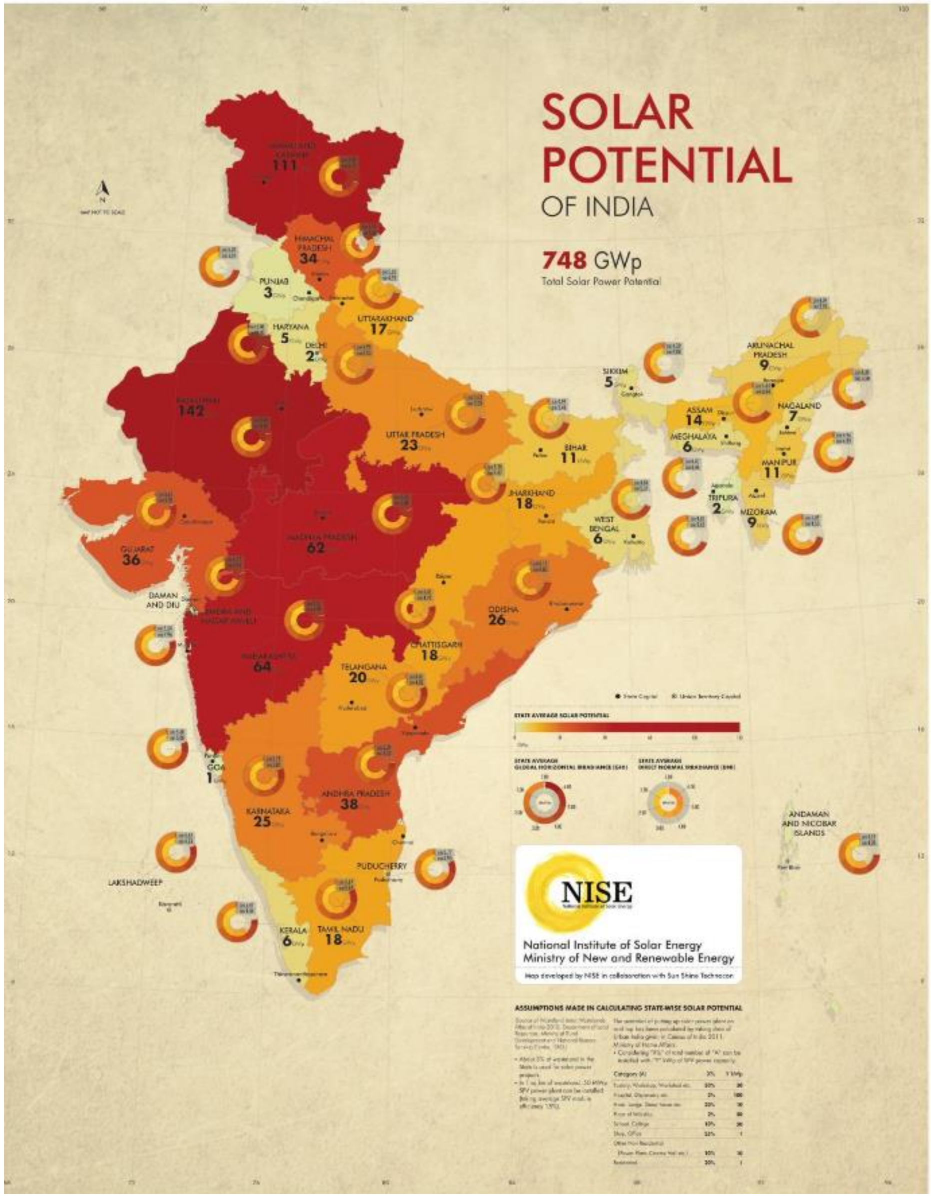


Figure (20) Solar potential of India [*Source: NISE and MNRE, India*]

2.5.2. Wind energy potential

India has a significantly large potential for electricity generation onshore wind, and a seemingly larger unexplored potential for offshore wind. The technical potential for wind power generation in India has been estimated to be around 50 GW at 50m height and 102 GW at 100m heights. As per preliminary estimations, over 120 GW of potential for offshore wind generation exists along the Indian coastline, thus special measurement stations have been set up in designated development zones by the GoI in the Western and the Southern Regions of the country. The National Institute for Wind Energy (NIWE) (s)(u) and the MNRE made a study on the on shore and offshore wind energy potential in the country[24][47], and the overall estimate at 50m and 100m heights were respectively published.

2.5.2.1. Onshore potential

Onshore wind energy potential in India has been recognized early, as India always considered energy from wind as an option. The initial steps to integrate wind power in to the Indian electricity sector began in the latter half of the 1980s, mainly due to the oil crisis earlier and the first substantial capacity showed up in the Indian power plant mix in the early 1990s. Onshore wind power in India has grown a lot, especially in the last decade, as it was heavily subsidized by the GoI. Several private investor companies invested in large wind farms in rural areas and in regions with a significantly large observed potential and smaller population.

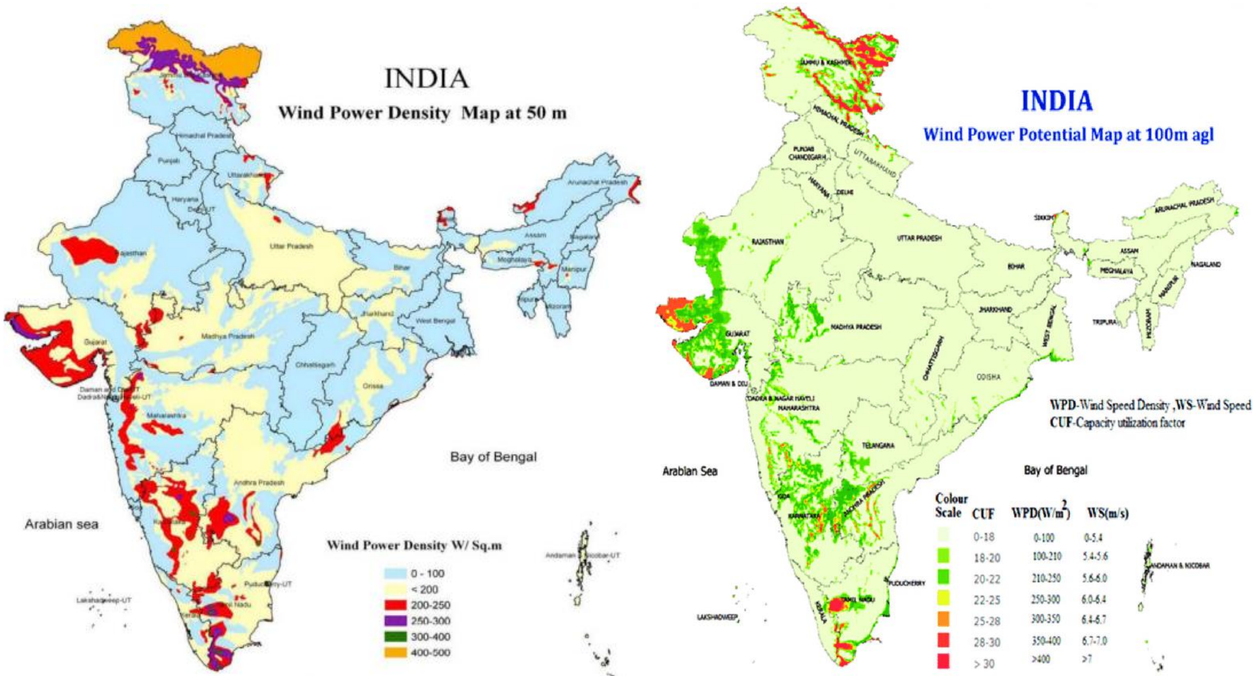


Figure (21) Wind resource potential maps for India measured at 50m (left) and 100m (right) respectively. [*Source: NIWE, GoI*]

The Figure (21) shows the availably of wind at 50m and 100m respectively, with the wind-rich areas significantly falling in the southern and western part of the country. Unfortunately, the northern region of wind rich Kashmir is currently disputed territory between India, China and Pakistan, and hence no such measures to tap this potential has been planned by the GoI. The geography of the southern peninsula offers a wind 'corridor' in the central region of the peninsula, which causes it to be windy almost throughout the year. Every year, with the arrival of the timely 'monsoon', the availability of the wind in this region significantly increases, thus the generation from wind accordingly. The wind power generation in the Southern region is higher in the time period July-October than the rest of the year, and this is also the 'rainy' season which can be assumed to be cloudy. Thus, the availability of wind compensates the non-availability of solar PV generation in this region. The total estimated potential for onshore wind in India was estimated to be around 150 GW, which is significantly lower than the observed technical potential for solar PV in the country. In the scope of this thesis, around 30 GW of planned capacity extensions are implemented in the aggressive RE expansion 'RES' scenario.

2.5.2.2. Offshore potential

With 7500 kilometres of coast, the Indian peninsula has one of the largest coast lines in the world. Thus, even with a safe estimation, the amount of unused offshore wind potential for power generation is also significantly one of the largest in the world. Several measurement stations in various regions and at different heights have already been installed along the Indian coastline, for a much more accurate representation of the available potential.

However, with the unique geography of the north-eastern part of the Indian peninsula, the region is subjected to heavy periodic storms and cyclones during the late months in the year. Thus, no such development zones have been identified in the eastern coast line of the country. With international territorial disputes with the country Pakistan in the north west, most of the north western coast has been excluded in the development zone designations.

The GoI has planned to implement around 1GW of offshore wind capacity as 'test' capacities, in the western and the southern development zones.

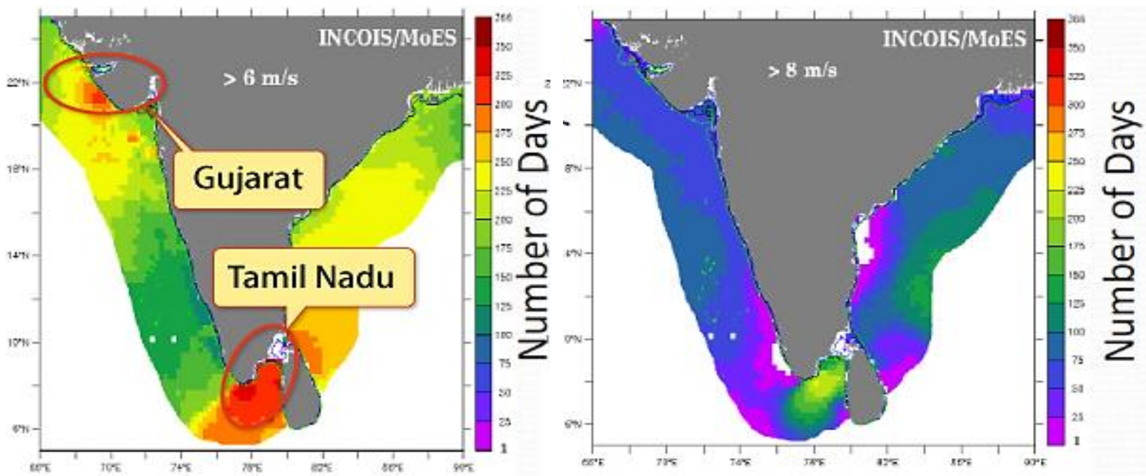


Figure (22) Offshore regions along the Indian coastline illustrating number of days where wind speeds are > 6m/s (left) and > 8m/s (right). [*Source: NIWE, ESSO-INCOIS*]

The NIWE has published a report on the plans for offshore wind power development in the country, and a rough estimated technical potential of 127 GW has been estimated. The figure (22) shows the various development zones for offshore wind power development in the country, and an estimate of the wind speeds in the region.

The power plant capacities of offshore wind implemented in ATLANTIS_India are all located in the most favourable locations as seen in the Figure (22). Around 3 GW of offshore capacity is implemented in two RES based scenarios defined in the scope of this thesis.

2.5.3. Biomass and energy crops potential

Traditional biomass usage for space heating and domestic usage has always been one of the prime sources of domestic energy in India. Even gasification of agricultural waste and usage in domestic heating is seen almost in every rural area in the sub-continent region. However, electricity generation from biomass has always been neglected, and only a few test or pilot projects were actually realized. With the increased concern over energy access especially rural areas, small capacities of biomass fired generation capacities were tested out in an attempt for sustainable decentralized electricity generation in small rural communities. Several pilot plants were installed in villages in the Northern and Western regions, and a dependent community of neighbouring villages set up. However, the idea of decentralized electricity generation from biomass never really took hold, with these few energy communities being the only regions where it was implemented.

India has a large potential for biomass resource, especially in the form of organic agricultural waste. As discussed before, almost 20 percent of India's electricity demand comes from the agricultural sector. A study on biomass availability in India [48] gives us a representation of the biomass potential from crop residue in India. Electricity generation from biomass could be a very important option for India as it is also considered to be a DRE source, with a more stable electricity generation characteristic. Several wastelands in India are either left alone or treated as garbage disposal sites, and these areas could be sustainably used to grow fast growing energy crops, to compensate for the large variations in availability of agricultural wastes resulting from the seasonal crop cycles. The implementation of biomass as RE capacity has been planned in the decentralized energy strategy by the GoI and MoP for renewable power in India.

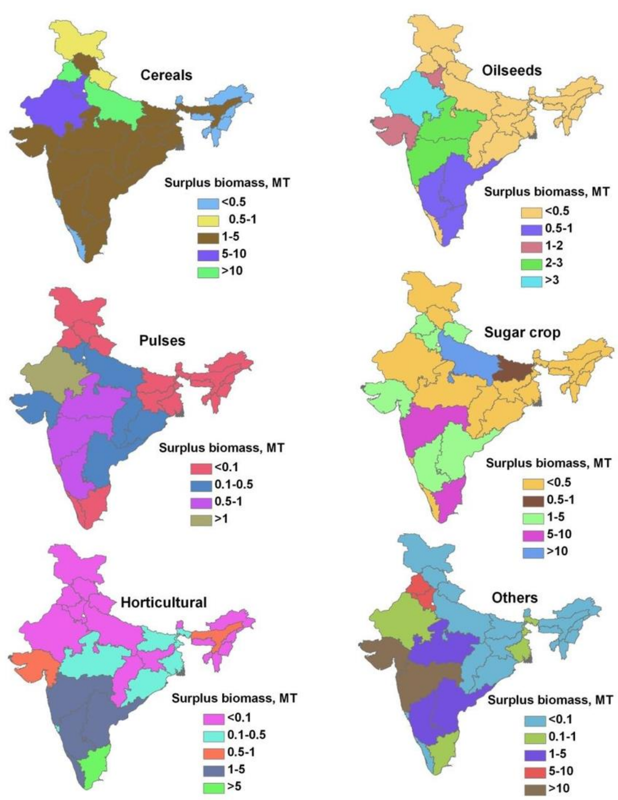


Figure (23) Bio energy potential from crop residue in India. [*Source: Hiloidhari, Das, Baruah et.al*]

2.5.4. Small Hydro Power (SHP) potential

India faces many challenges and roadblocks for the development of large hydro power within the country, and in the sub-continental region. However, there exists a large potential for small hydro power, in almost all regions throughout the country. The GoI has also heavily subsidized the small hydro sector, allowing small private investors to build small hydro capacities (less than 1 MW capacity) on their private properties. Several small hydro projects popped up after the implementation of these subsidies in the beginning of this decade.

The potential for small hydro power in India has been estimated by the MNRE to be as large as 15 GW, in 2012. Based on the technical and economic viability of the building of small hydro projects, the MNRE has also identified around 5000 sites covering a potential of over 14 GW. The regional state governments of 23 states in India have so far announced support schemes and policies for private investment in small hydro power capacity [49]. The Table (1) shows the unused potential for small hydro power in India. A study [50] conducted at the institute explored the possibility of a hydro power plant with 'deferred' status in the North Eastern region of the country, to be replaced with small hydro power capacities adding up to the total generating capacity of the deferred plant. This study conclusively showed the effectiveness of the replacement idea, with almost no observable environmental impacts.

1	Estimated potential	15000 MW
2	Identified potential	14,305.47 MW
3	Installed capacity	2429.77 MW
4	Capacity under implementation	483.23 MW
5	Identified sites	5415

Table (1) Table highlighting the estimated, identified and used potential for small hydro power in India. [*Source: MNRE*]

Several studies have analysed the diffusion of small hydro power capacities [51] in India, and is as shown in the Figure (24) below. The diffusion curve is characterized by a slow initial growth (from the early 90s), then followed by a rapid growth (2010 until the year 2030), and is expected to saturate by the year 2030. This is under the assumption of the improved subsidies for small hydro capacities in the potentially rich regions aggressively promoting the increase of small hydro power capacities in the respective regions.

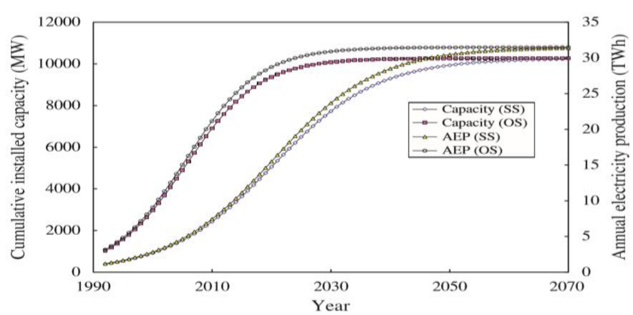


Figure (24) Small hydro power diffusion in India [*Source: Purohit, P. et.al, Energy Policy (2008)*]

2.5.5. Others

Waste management in India has always been a sustainability problem, especially in the rapid growing urban areas in the country. Testing of energy generation from waste has been implemented, in the form of biogas from sewage, in the respective treatment plants in few urban regions. However, the share of biogas used in electricity generated is usually used to sustain small rural communities. Major electricity production based on organic- and inorganic- waste from urban cities could be implemented as a sustainable solution to the ever-growing challenge of waste management in the country. The implementation of smart city challenge by the GoI brings in incentive for the city administration to come up with smart solutions for the development of their respective urban areas, and several plans to set up electricity generation via organic waste have already been proposed. Sorting of organic garbage separately in households is already a compulsory rule in many cities now, and the organic waste is usually used in the generation of biogas. The biogas generated from the organic waste can be treated as renewable energy.

CHAPTER 2

Modeling of Indian Electricity Economics

3. ATLANTIS_India: Techno-economic simulation model

It is obvious that the transition of the electricity sector in the Indian sub-continent region needs strategical planning and exploration of technological and economic impacts. A techno-economic simulation model would prove really effective to simulate all the possible scenarios defined for the region.

ATLANTIS_India [7] is an elaborate, complex-but-simple techno-economic simulation model designed and developed to simulate the Indian electricity sector. In the initial stage of the development of the simulation model, only the electricity system of India was considered. In the later development stages, the electricity systems of several neighbouring countries were eventually added, as it was recognized that the electricity sectors of these countries are already, and will be, closely related and interdependent in the coming years. It was found that several energy strategies of the Indian electricity sector included investments in and improvement of the electricity systems of the above-mentioned countries. The model ATLANTIS_ India is thus a specifically designed model to emulate the electricity economics of the Indian Subcontinent region.

The motivation for the development of the model is the techno economic and social welfare of all the countries in the electricity system of the Indian Sub-Continent. The regions included in the simulation model are as follows: India (five power regions), Bangladesh, Bhutan, Nepal and Sri Lanka. The power regions Pakistan, China and Myanmar will have to be eventually added, as currently due to political situation and conflicts, there are no actual or proposed interconnections between these electricity systems and India. The national strategies of all the regions included in this model are carefully studied, to identify the parameters connecting all the regions into one whole electrical network – if not in the present, but based on the future projects envisioned by their respective cumulative national strategies.

Several studies have been completed in the scope of the development of the simulation model. Scenario specific studies for the development of real-life scenarios for the region, demand projection studies to evaluate several different demand trends and on the additional demand resulting from e-mobility strategies proposed in the region. The overall completion of the simulation model clearly justifies the massive amount of the effort involved in the development, in the initial data collection, data evaluation and validation and the subsequent simulation of specific scenarios. The following chapter briefly describes the simulation model, mentions the wide range of simulation options for specific market types and also the wide spectrum of possible simulation results.

3.1. Introduction: ATLANTIS_India

The model ATLANTIS_India is based on the techno-economic simulation model ATLANTIS [8] which was developed at the Institute for Electricity economics and Energy Innovation, at the Graz University of Technology. The model is a complex system of input data-, database-, calculation- and output modules, each connected with the other with their respective relationships, by specifically defined ‘keys’. These keys are defined to transmit data either one way or both the ways between two modules, based on the necessity and the requirements. The several modules involved, and their respective functionalities are as shown and described eventually in the Figure (25).

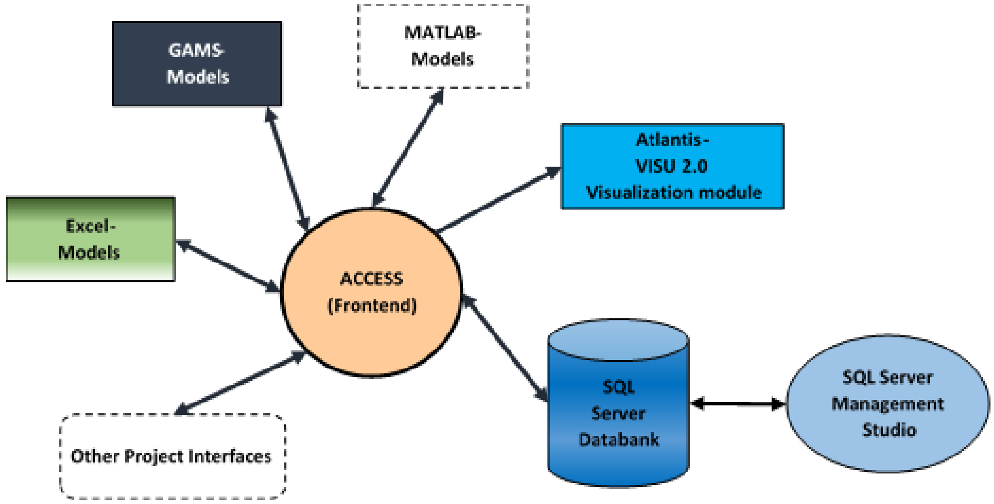


Figure (25) Module structure and the data flows in the model ATLANTIS_India [*Source: ATLANTIS, IEE*]

The several modules used in this model are described thoroughly as follows

1. GAMS modules
2. MATLAB modules – Scenario development tool (in development)
3. Excel Modules
4. Visualization Module
5. SQL server Database
6. SQL server management studio
7. Other project interfaces – includes e-mobility module (in development)

The input, output and other necessary data are stored in (temporary) excel files as tables. There are three types of tables used in the Microsoft excel module: 'Tbl_Stamm_', 'Tbl_Param_', and 'Tbl_SZ_'. 'Tbl_Stamm_' tables are designed to hold all of the relevant important input data required for the model to function. This involves the definition of regions, nodes, transmission lines, power plants, power plant types, demand and many more. The 'Tbl_Param_' are the excel tables design to hold the parameters required for the calculation of specific variables like economic prices, power plant investments, lifetimes, and many more. Finally, the 'Tbl_SZ_' excel tables are designed to hold the Scenario definition parameters, which can be altered to change the simulation scenario. Parameters like scenario specific fuel prices, growth rates, regions to be included and many such data.

Once all the data structures and tables are completely filled, the simulation calculations can be completed for each year until the defined target year. The simulation target year is usually defined with the availability of futuristic data, in terms of energy strategies and national energy policies. For the scope of the thesis, the base year for all simulations are defined to be the year 2006, input data up to the year 2017 are validated with respect to several relevant databases and published documents, and the target year is set as 2050. The simulation run can be accurately described with a flow chart, for the understanding of how each simulation run returns values and how an overall simulation until the target year actually takes place. The Figure (26) shows the flow chart describing the simulation run and the processes involved in each step of the simulation run of the model.

The definition of a scenario is based on the database (SQL server), which includes the master data (Stamm_) on power plants, networks, companies and consumption. Additionally, this scenario definition is based on a regional level and includes different economic parameters such as fuel prices, construction cost indices, consumption growth rate and several other relevant parameters. Based on a completed and fully consistent scenario framework, scenarios are to be simulated in the model.

At the beginning of the simulation, a demand coverage check for the annual and summer peak load takes place. If the available power plant capacities are insufficient, automatic power plant addition can be carried out, provided when necessary. Once the demand coverage in the simulation is sufficient, a monthly loop is started with the energy coverage, load flow, and re-dispatch calculations for the user-configured peak and off-peak periods. Following the monthly energy coverage of each month in the designated year, the annual financial statements for each model region are generated. After the end of the successful (can also include unsuccessful) simulation, the results are displayed and processed via the database as well as the graphical representation in the visualization module ATLANTIS VISU 2.0.

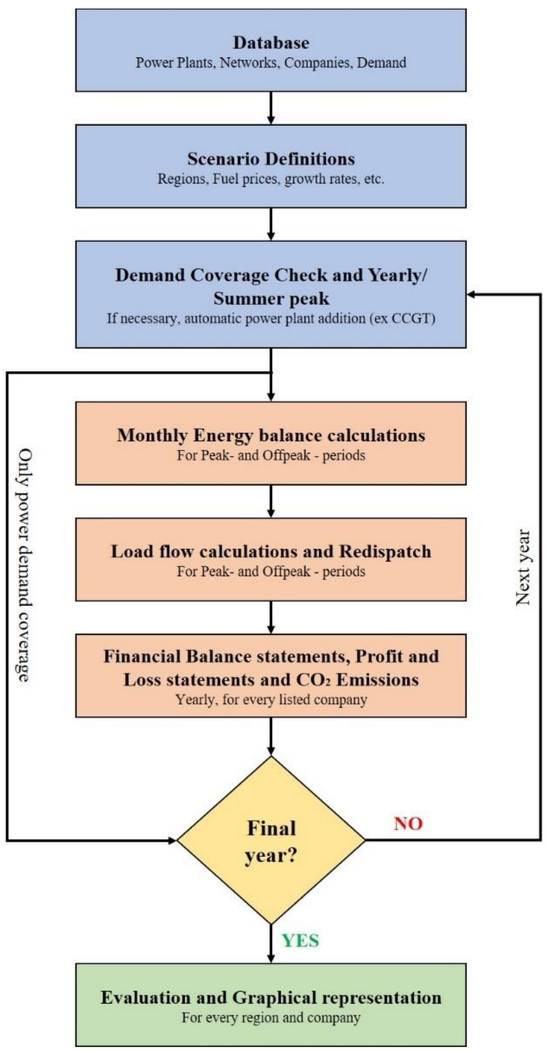


Figure (26) Flow chart describing the simulation run of the model ATLANTIS_India [*Source: ATLANTIS, IEE*]

3.2. Simulation model ATLANTIS

The simulation model ATLANTIS is a techno economic simulation model for the pan-European electricity economics developed at the Institute of Electricity Economics and Energy Innovation, Graz University of Technology. The development of this massive simulation model included around 50-man years with contributions from several doctoral dissertations, master and bachelor theses. ATLANTIS_India is closely based on the model ATLANTIS, mostly replicating the simulation structure and market modelling. The model ATLANTIS now covers the electricity economics of majority of the mainland Europe, the Nordic regions, the Balkan region, Turkey and North Africa. Specific analyses of new transmission infrastructure, power plant scenarios, economic scenarios and input-output analyses can be conducted in the scope of the simulation model ATLANTIS.

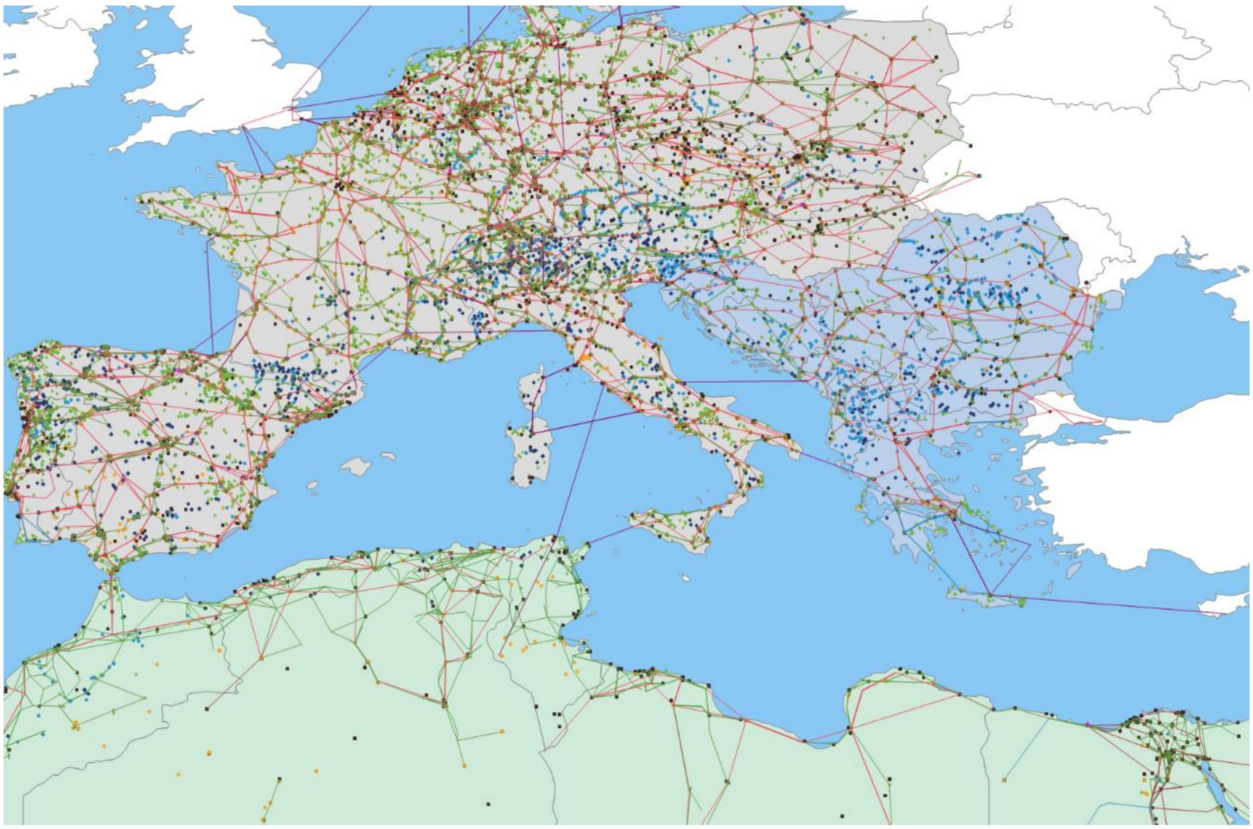


Figure (27) The techno-economic simulation model ATLANTIS [*Source: ATLANTIS, IEE*]

3.3. Physical modelling in ATLANTIS_India

The physical model for the simulation model consists of physical model elements like demand center nodes, transmission lines, power plants, transformer stations and phase shifting transformers. Each power region is modelled carefully based on their power maps and several opensource and PLATTS power plant databases which have been used for development of the physical model. The geographical accuracy of the physical elements involved in the model have been manually validated, with the help of these specific power maps in reference to google maps. Also, by carefully studying the national strategies for India, Nepal, Bangladesh, Bhutan and Sri Lanka, the proposed long- and short-term transmission projects, especially those of which are cross border transmission capacities, are seemingly carefully integrated. Similarly, India's proposed investments in hydro power capacities in Nepal and Bhutan are also considered, along with investing party and the ownership regulations. A visualization of the physical model of ATLANTIS_India is as shown in the Figure (28)

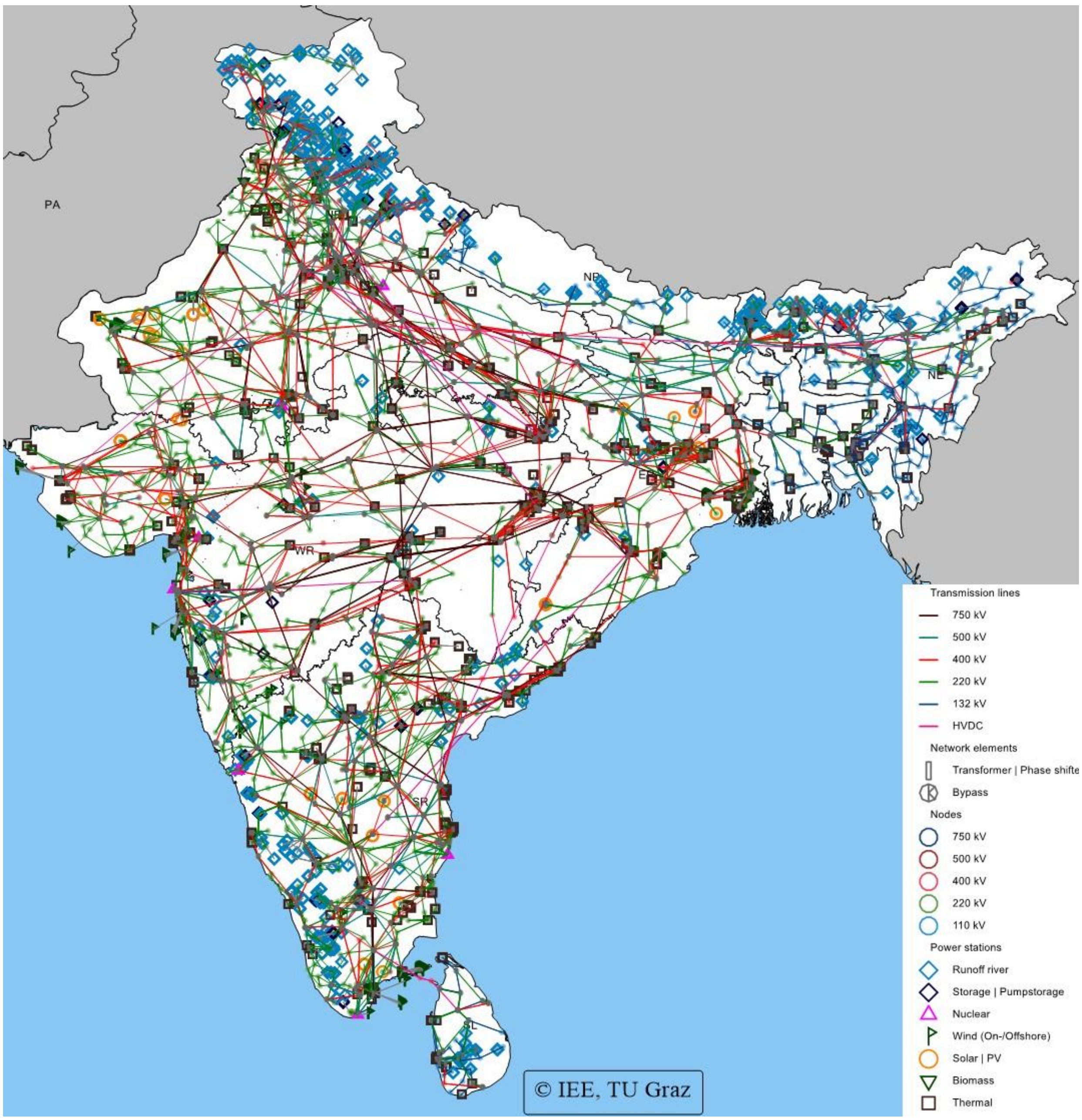


Figure (28) Visualization of all the physical components in the simulation model ATLANTIS_India

The physical model of ATLANTIS_India can be clearly understood, by describing the definition, classification and understanding of the following physical components.

3.3.1. Model Regions

The Simulation model ATLANTIS_India is designed to simulate the several connected power regions (present and possible) in the Indian sub-continent region. The five official power regions in India: East Region (ER), North Region (NR), North-East Region (NE), South Region (SR) and West Region (WR) form the main part of the physical model. The neighbouring countries of Bangladesh (BA), Bhutan (BH), Nepal (NP) and Sri Lanka (SL) are included as model regions in ATLANTIS_India, as the energy policies in these countries and the Indian energy policies are usually found to be interdependent. A visual representation of the model regions and its surroundings can be seen in the Figure (29)

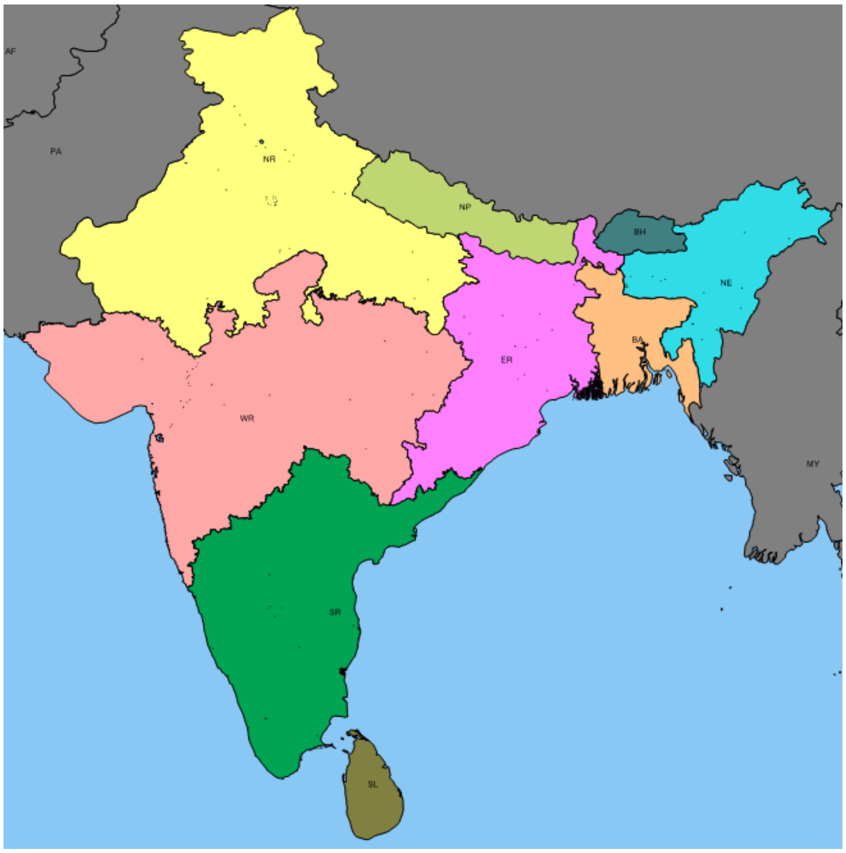


Figure (29) Model regions in ATLANTIS_India

3.3.2. Demand centres: substation nodes

A 'Node' in ATLANTIS_India defines a demand center connected by at least two transmission lines. This also represents the subsequent substation connecting a transmission line. The overall demand of the region is carefully distributed among major nodes based on the population density, industrial areas and agricultural areas which will be discussed more in detail in the description of demand modeling later. However, even when some nodes have no demand weightage, they can act as feed in points for nearby power plants, thus connecting the generating stations to the overall transmission network. Several nodes with minimal demand weightages are defined as futuristic feed in points for planned capacity expansion at that particular location.

The definition of the nodes, for each region, has been done with the 'Tbl_Stamm_Knoten', which contains the information on a unique Node ID for each node, their geographical location, the voltage levels at the nodes i.e., the voltage level of the transmission lines meeting at this specific node, and the demand weightage. The information of additional demand, when available, can also be distributed by assigning additional weightages, across the whole region. All the nodes are assumed to be operational in the year 2000, for the sake of simplicity in the model. The Figure (30) shows the node representation with various voltage levels across different regions in the sub-continent.

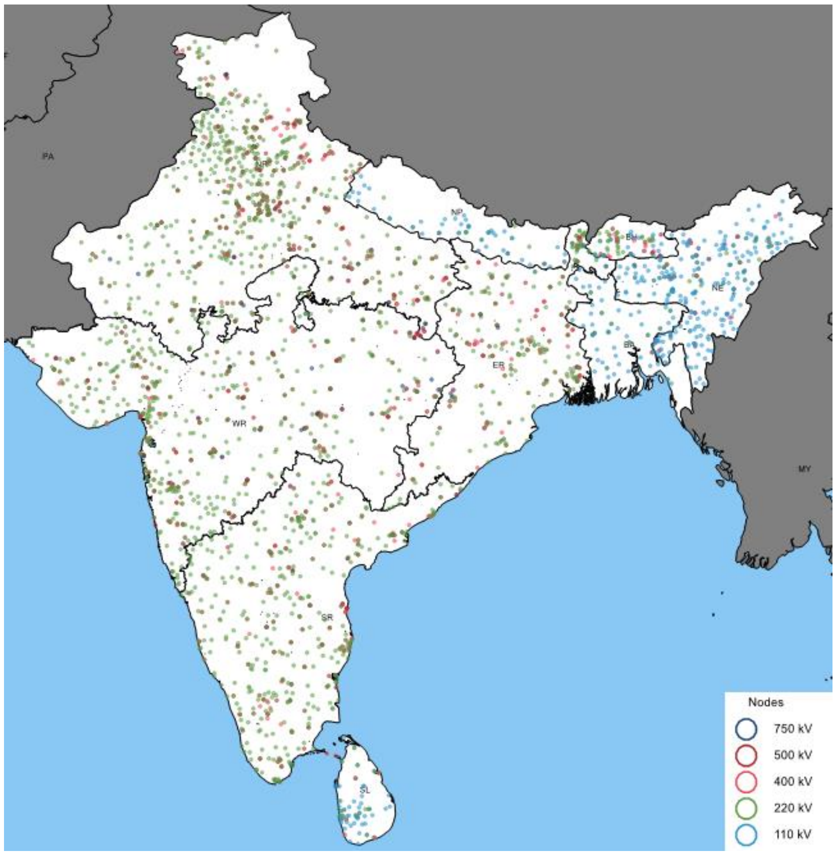


Figure (30) Representation of the nodes in the Indian model

Overall, around 2926 nodes have been defined in the model, 400 at the 132 kV level, 1547 at the 220 kV level, 573 the 400 kV level, and 119 the 765 kV level. Around 287 nodes at 500 kV level are also defined, representing the substations connecting the 400 kV quad lines (operational at 400 kV, defined to be at a higher voltage level), for the sake of simple differentiation. Most of the demand centers are represented usually by two or more nodes, it is obvious that the transmission lines of different voltage levels are coming in to the node. The geographical location of each node was confirmed with the use of google maps satellite images, where the substation in the vicinity was identified manually and used to define the node. Usually, nodes acting as power plant feed in points are usually at the lowest voltage level available at the particular node, since the demand weightage at each node is assigned to the lowest voltage level.

3.3.3. Transmission network and transformer stations

A transmission line in ATLANTIS_India is represented as a straight pathway transporting electricity from one node to another at a particular voltage level, in the electricity system. In this model, six different lines, based on transmission technology types and voltage levels have been defined. The voltage levels available at a particular node is decided by the voltage levels of the transmission lines passing through the node. The transmission lines in the model are defined using the transmission voltage level, the resistance rating, the inductance rating, the capacity rating, the defined isothermal capacity and finally the calculated power transmission capacity. ATLANTIS_India generalizes the classification of transmission lines in each model region based on the transmission voltages.

The six different transmission levels defined in the physical model are

1. 132 kV AC
2. 220 kV AC
3. 400 kV AC
4. 500 kV DC
5. 765 kV AC
6. 110 kV HVDC

The transmission lines are defined as an input to the model in the excel table 'Tbl_Stamm_Leitungen'. Each region has a power map defined by the TSOs operational in the region, and such a power map is used to map out the transmission lines in the model. After defining the nodes, the transmission lines are defined between two specific nodes at the same voltage levels and are labelled with unique transmission line IDs. These IDs actually contain information on the voltage levels of the transmission line defined. It is important to define the physical and thermal capabilities of the transmission lines with a high accuracy, as these parameters play an important role in setting physical restrictions later on, during the calculation of the load flow possibilities. Whenever the data for the line is not available, standard values are to be assumed based on the information from the CEA and ENTSO-E.

The data on transmission line distances, when not available as published data, are calculated based on the straight-line distances between the geographical positions of the respective nodes connected by the lines, with a 10 percent increase to account for existing deviations. Once the transmission lines have been defined, they form the basis for the power plant addition in to the model. A Figure (30) shows the actual representation of the transmission line system of the Indian subcontinent. The regional differentiation of the transmission networks of each model region has also been done in the later part of this chapter.

In the physical model of the Indian Subcontinent, a total of over 6000 transmission lines have been defined, as it can be seen from the visualization in the Figure (31). Around 800 lines have been defined in the 132 kV AC level, 2992 in the 220 kV level, 1339 in the 400 kV level, 505 in the 500 kV and 264 in the 765 kV AC level. 24 of HVDC lines connecting generation rich regions to demand rich regions are also defined. The ownership and investment costs of the transmission lines has NOT been defined, and they are assumed to be operated by a single regional Transmission System Operator. This assumption can be justified, as there are only small number of (in comparison) transmission lines owned privately, and the regional TSOs are just divisions of the central power sector.

The load flow calculations for load flow in the transmission lines follow a ‘DC-Optimal Power Flow (DC-OPF)’ approach [52], based on linear DC load flows. This provides a linearized optimization of the grid state. Thus, considerations to only the ‘active’ power flow have been given, and the justified assumptions are carried out when evaluating the AC load flows. For the effective and useful utilization of the DC-OPF method, certain rules or the definition of transmission lines have been included. The ratio between the series reactance (X) and resistance (R) of the network is defined to be not less than the factor 4. The maximum phase angle deviations for the transmission lines are also defined, at 0 degrees for the AC lines, HVDC lines which are defined with a phase angle tolerance of 20 degrees. The use of DC-OPF approach for load flow calculations is to ensure faster calculations, especially when applied to very large systems like ATLANTIS and ATLANTIS_India

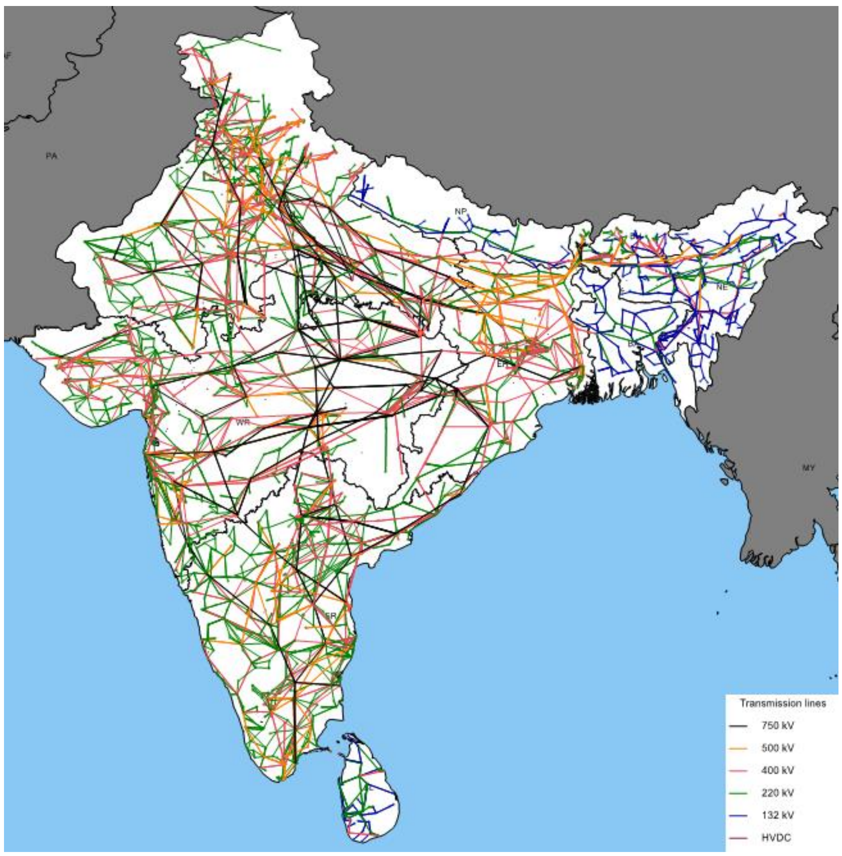


Figure (31) Representation of the transmission lines in the model

The transformer stations in ATLANTIS_India are defined as transmission lines of zero length, connecting two nodes of different voltage levels at the same location. These are really important to be included as the voltage step up and step down between transmission levels are done by the transformers by definition. Specific cases where the transmitted power has to be controlled for power quality, phase shifting transformers would be necessary. These phase shifting transformers are also defined in the model, with reference to data availability in the regional power maps, and as per required by the simulation runs. A phase shifting transformer is defined with a maximum phase angle tolerance of 45 degrees, for accommodating the power transmission. The transformer power capacities are also to be defined, as they play a vital role in calculation of resulting load flow in the transmission lines of two different voltage levels. Transformer stations are to be defined along with the transmission lines in the excel table ‘Tbl_Stamm_Leitungen’ as input data, as they are considered to be transmission lines with zero distances.

A Figure (32) shows the transformers defined as physical elements in the model, each grey marker describing a transformer defined between two voltage levels at the same node.

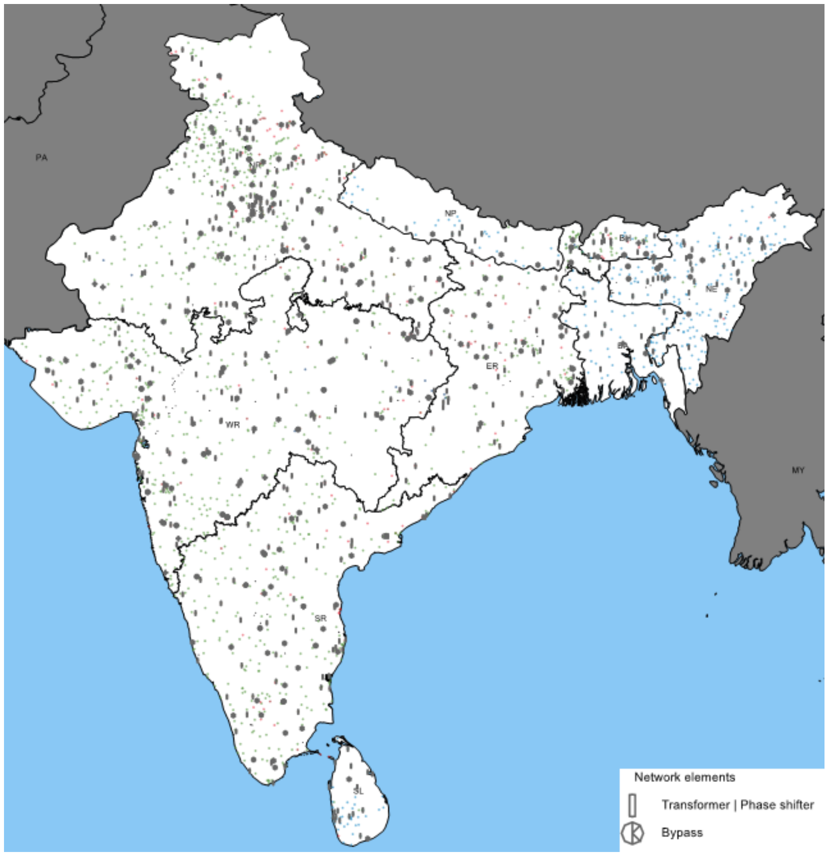


Figure (32) A visual representation of the transformers in the transmission network in the Indian subcontinent

Overall, around 900 transformers and 250 Phase shifting transformers have been defined in the physical model, and sufficient thermal capacities have also been assumed to ensure a smooth operation of the network model. Short Circuit Lines or Shorting lines (KSB) are also defined, when and where necessary, if the transmission lines end at a particular node location with minimal or zero demand weightage.

3.3.3.1. Regional analysis of the physical model: uniqueness and importance

A look at the region-specific physical transmission model gives us a detailed understanding on each of the power regions/countries in question. A large network of high voltage lines would mean that the region hosts a large concentration of either generating capacity and/or demand centers, giving a measure of the improvement of electricity systems in the said region. For example, a vast network of 132 kV lines crisscrossing the regions of BA, BH, NP, NE and SL in a strong contrast to the other regions of ER, NR, SR and WR. The weak transmission infrastructures in the above said regions, can be an indication of the smaller developments in the electricity system in the regions. A proposed reinforcement of weak grids has also been considered in this thesis, thereby accommodating an increase in power plant capacity in the region.

a. East Region (ER)

The ER is the region that has seen the highest development in the expansion of generation capacities, transmission and distribution infrastructure since the last decade, with several new transformer substations and high voltage transmission lines being constructed. Once the availability of cheap domestic power generation grade coal in the region was confirmed, mines were opened and subsequently large capacities of coal powered plants were installed, with the major priority of electricity export in mind.

Thus, along with a vast network of 220 kV lines, a similar share of 400 kV lines can also be seen in the region. Most of the high voltage network in the region were built in the recent years, and hence can be expected to have a better performance than the networks in most other regions. Almost all of the regional interconnections with the other power regions are via the 765 kV AC network, as the main priority of the electricity sector in the region is to transport generated electricity towards demand rich power regions like the NR, the SR and the WR regions. With the purpose of forming an electrical high way in mind, the ER is connected to NE region via Bangladesh, with high voltage interconnections at 400 kV level, for the easier possibility of redispatch through the whole region. Interconnections with 400 kV quad lines (500 kV lines) with the BH region and 400 kV with the NP region are also planned to better accommodate the electrical power transfer in the region. This is in terms with India's proposed investments in the BH and NP regions.

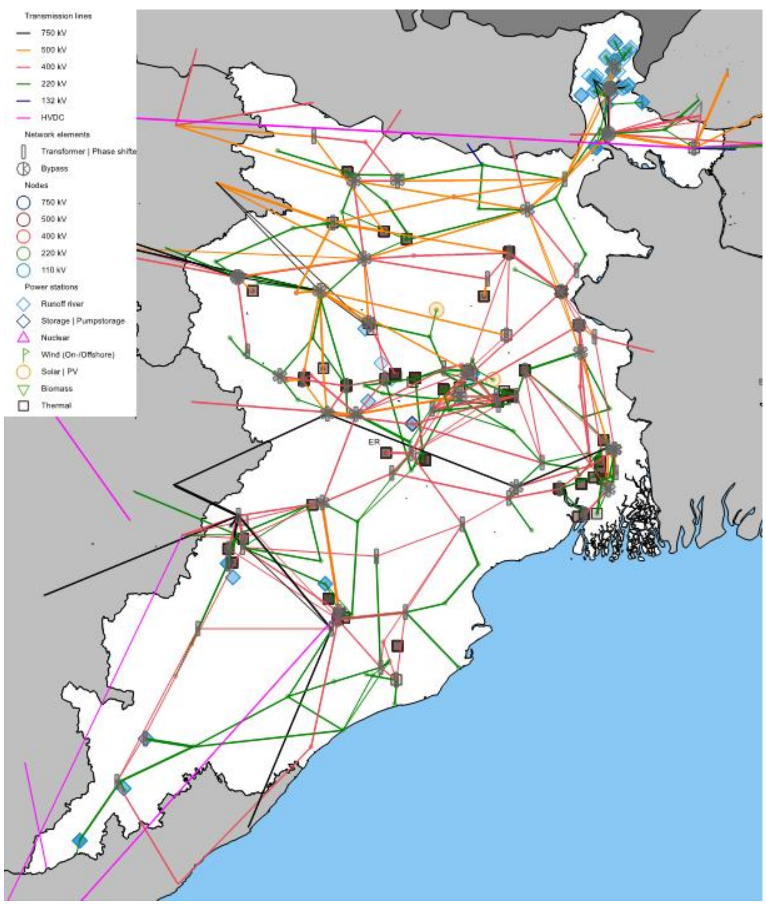


Figure (35) Visualization of the transmission network of East Region

b. North East Region (NE)

The NE region, rightly dubbed as the ‘power cradle of India’ is the region with the highest unused potential for hydro power. This potential identified in the NE region, is unfortunately the least utilized one, regarding the several inter-state and international territorial and water sharing disputes. This region hosts a large number of planned, deferred, cancelled or delayed large hydro power plant projects. However, with the region having access to cheap gas from Bangladesh, most of the power plants capacity in the NE are gas-fired capacities. These gas-fired capacities are built close to the demand centers in the region. Thus, with this situation, and the highly varying topology of the region, the improvement of transmission infrastructure has been mainly neglected in the region. Recent improvements with regards to HVDC infrastructure is due to the planned commissioning of several centrally-owned hydro power plants north of the region.

The recent industrialization spurt in one of the states comprising the NE region has given rise to a large increase in electricity demand, thus the lack of generating capacities forces the region to import electricity from BA and ER regions. The region has a very poor development in the transmission network, and a large part of the old 132 kV transmission network can be still found. The regional TSOs merely maintain it, rather than upgrade the network to a higher and better voltage level.

However, with several large hydro power plants planned in the region, and regional and interregional interconnections with Bangladesh and Bhutan proposed, the region has seen an increased improvement in the construction of the 220 kV and the 500 kV DC network as seen in the representation below. The remote geographical location of the NE region (BA almost separates NE from the rest of India), makes it significantly necessary to build high voltage infrastructure, to ensure a smooth integration to the rest of the Indian power grid. Almost no RE capacities are planned in the region, with regards to the really low observed potential, in comparison with the rest of the regions.

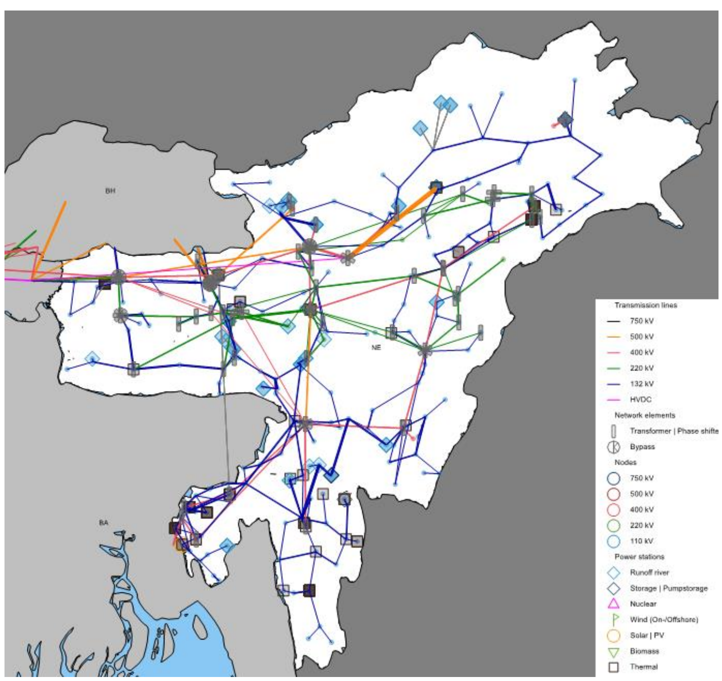


Figure (34) Visualization of the transmission network of North East Region

c. North Region (NR)

The NR is home to the largest capacity of hydro power plants, in comparison to all other regions. In this model, most of the larger power plants (both conventional and unconventional) feed in electricity to the lowest possible voltage level available at the given feed in node. Most of the larger power plants are connected to demand centers with newer 400 kV infrastructure, with higher thermal capacities and better efficiencies. Therefore, the 400 kV AC network in this region is very prominent. This is also seen from the visual representation of the region. The 220 kV network, forms the basis for the distribution network, where the voltage is stepped down from 220 kV to 66 kV at the specific substations. Thus, it can be seen with most regions, there is also a vast network of 220 kV lines. Also, since the NR is initially an import dependent region, several HVDC lines are planned from the ER, NE and WR regions. All the HVDC lines converge around the Delhi area, which is the largest demand center in this region. These lines connect the coal power plants, solar PV and hydro power plants to the demand rich Delhi area. Most of the hydro power plants can be seen connected by the 400 kV network in the region, especially at the north of the NR, in the Himalayan mountain region. Coal and gas power plants evenly distributed close to demand centers, solar PV in the waste lands in the west, and a small number of wind plants in the north western part are connected by the 220 kV network. This shows the improvement of long-distance transmission infrastructure in the region is revolving around the effective integration of its hydro power plant capacities.

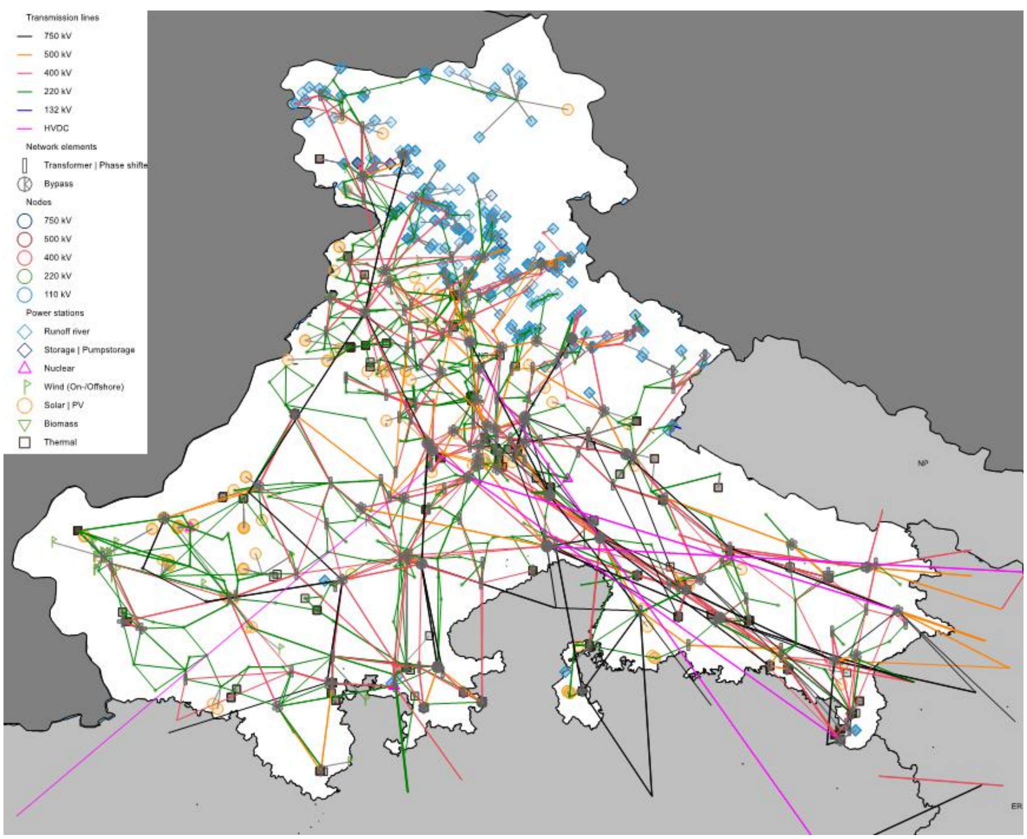


Figure (33) Visualization of the transmission network of North Region

d. South Region (SR)

The SR is the region with one of the most diversified power plant portfolios in the sub-continent. Furthermore, due to recently announced subsidies and support for RES, the SR now has one of the highest shares of solar PV and Wind power installations in the region. The region also hosts a significant nuclear capacity, with four generating stations- of which one unit is the experimental Thorium HT-FBR reactor. Even with a considerable share of generating capacity, the region still remains import dependent due to several large demand centers, and thus has a strong interconnection between the ER and the WR regions, at the 765 kV level. Furthermore, in the year 2023, a proposed HVDC line will finally connect the isolated island system of Sri Lanka to the electricity system of the subcontinent, giving the opportunity for Sri Lanka to lose its dependency on oil-fired generating stations on barges. This also provides India with the option of flexibility, as the wind and hydro potential in Sri Lanka is considerably large, and the country can access carbon free energy from the SL region with ease.

The region has a vast network of high voltage transmission infrastructure, especially the newer 400 kV lines connecting all demand centers effectively. The 220 kV network also is expansive, connecting the diverse and large generation capacities to the demand centers in the region. Several 765 kV transmission lines have been proposed by the year 2025, to connect the newly planned solar PV, Wind (on shore and off-shore in 2030), and nuclear capacities.

The region SR is unique by its own right, as one of the only test regions for e-mobility has been established in Bangalore, one of the major demand centers in the south. This justifies the building of the HVDC lines from the ER to the SR, all leading to the Bangalore area. A visual representation describes the transmission network of the SR and the interconnections with its neighbours.

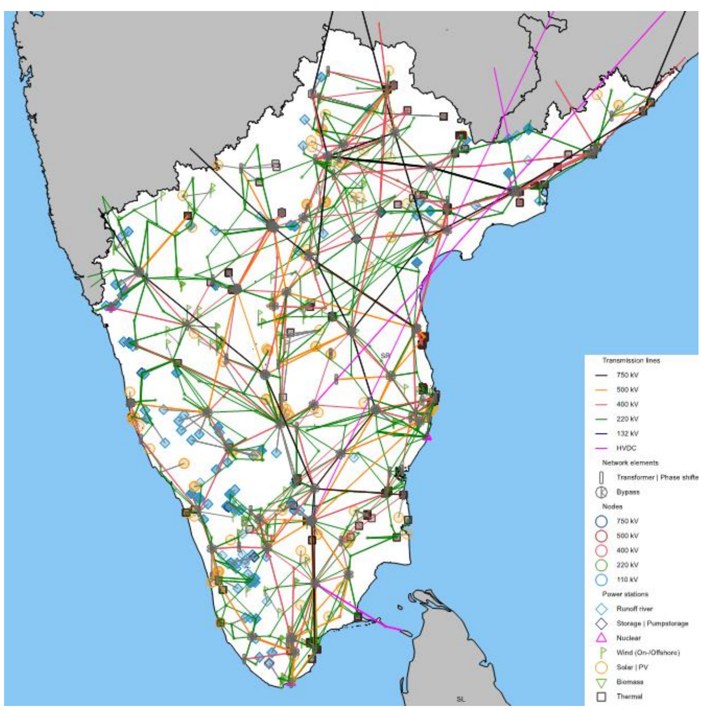


Figure (36) Visualization of the transmission network of South Region

e. West Region (WR)

The WR region has become the industrial capital of the country, and claims the largest share in the Indian industrial demand. The region has specifically shown a considerable increase in electricity consumption in the last two decades, with regards to the rapid industrialization in the region. The biggest city, both in area and population, Mumbai, is located in this region. The population density and the urbanization rate of Mumbai is also the highest in the country. Hence a large expansion of generating capacities was observed in this power region, with significant coal-fired and gas-fired capacities in the eastern part (availability of cheap coal) of the region. A large network of existing 220 kV lines were eventually reinforced with 400 kV infrastructure, to support the effective power transfer from the eastern part of the region (generation) to the western part (demand). Recently planned 765 kV lines not only ensure a stronger reinforcement of the network, but also support the effective interconnection of the region with the ER, NR and the SR regions.

Furthermore, the north western part of the WR has also observed rapid urbanization and industrialization as the several of the Special Economic Zones (SEZs) were proposed in the region. Thus, to cover up for missing capacity due to sudden increase of demand, a large gas-fired capacity exists in the region, and several new transmission infrastructures can also be observed.

Some of the larger solar PV generating stations were installed in the WR region, thus making the development of its electricity network an interesting one. Previously, the transmission network in the north western part of WR was of the 220 kV voltage level as most of the power plants were installed in the vicinity of the SEZs and Industrial areas. With the advent of RES capacity and coal-fired Ultra Mega Power Plant Projects (UMPP), long distance transmission became severely necessary and several 500 kV, 765 kV and HVDC lines were planned and constructed in a short duration of time. Also, plans for setting up a test area for smart grids and DSM in India are being chalked out in this region, as the WR is the region with the greatest number of upcoming cities.

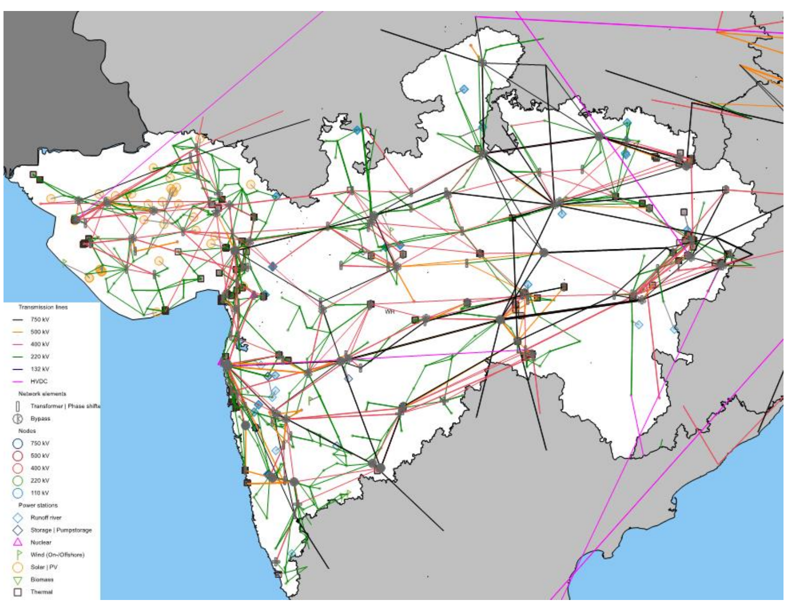


Figure (37) Visualization of the transmission network of West Region

f. Bangladesh (BA)

The BA region is in an interesting geographical position, occupying a land mass between two Indian power regions, the ER and the NE regions. The transmission network of the BA region plays a major role for the effective integration of the remote NE region with the other Indian regions. The development of the transmission infrastructure in the BA region is thus very lucrative to the Indian power sector, as it brings in the large possibility of flexibility and security to the overall Indian power grid.

The availability of natural gas resources in the country also makes the power region interesting in a power perspective, for India. In the North Eastern part of the BA region, a large number of natural gas fields can be found, and the availability of cheap natural gas can be confirmed in the area. Thus, India has always been interested with the overall development of the electricity sector in the BA region, and has participated in many of the investments for generating and also transmission infrastructures in the region. The south Eastern part of the BA region has a high untapped potential in Hydro power, and Nuclear power is also said to be introduced in the country in the coming decade.

The BA grid can be seen to be separated into two parts – the East and the West, by the river Ganges, and the two parts are interconnected with a 220 kV interconnection near the capital city Dhaka. This interconnection is to be further strengthened one the cross-border lines across the ER in India and Bangladesh has been completed. At the moment the only cross border interconnection BA has is with the NE region, in the east, where it exports cheap electricity from natural gas power plants in the vicinity to the NE region.

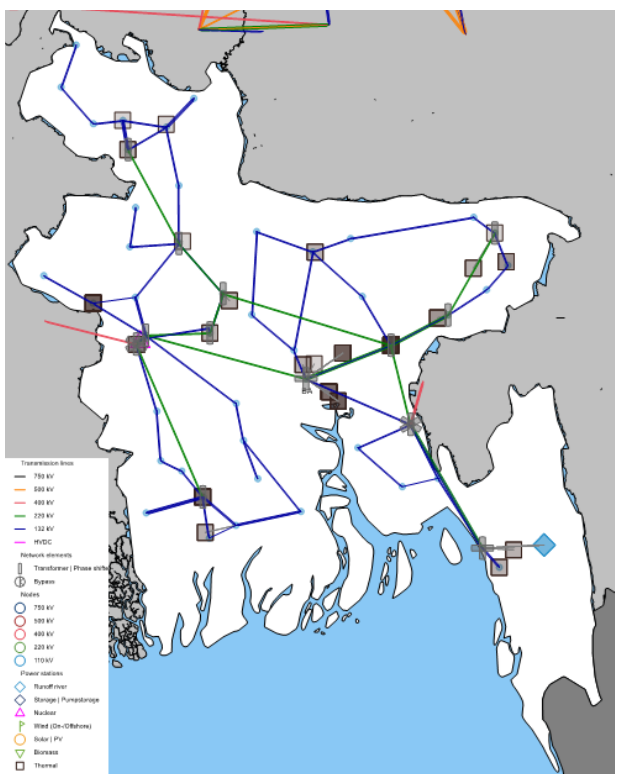


Figure (38) Visualization of the transmission network of Bangladesh Region

g. Bhutan (BH)

The political ties between Bhutan and India have always been good, and India has always taken a keen interest in the overall development of Bhutan. Several of Bhutan's available installed generating capacities were supported by India either with the investments or with the technology.

The visual representation of the Bhutanese grid shows the concentration of lines in the south, where most of the population resides. The transmission infrastructure is mainly on the 132 kV level, as a small population residing in the south are supported by few hydro power capacities in the north. Even the interconnections of the BH region with the NE region in India presently exists at a 132 kV level. However, because of proposed plans for installation of several new large hydro power plants by India in the region (already discussed), utilizing the vast potential in the northern mountainous region of the BH region. This, however, needs new long-distance transmission infrastructure from the north to the south, the subsequent upgrade of the electrical substations in the urban hubs, and also an improvement in the existing interconnections between Bhutan and India. Therefore, a large amount of high voltage 400 kV transmission infrastructure has been planned for the next decade, followed by gradual installations of large hydro capacities in the north.

Most of the planned and under construction hydro power installations are owned by the central government company National Hydro Power Corporation Limited (NHPCL), with shared ownership agreements with the Royal Government of Bhutan.

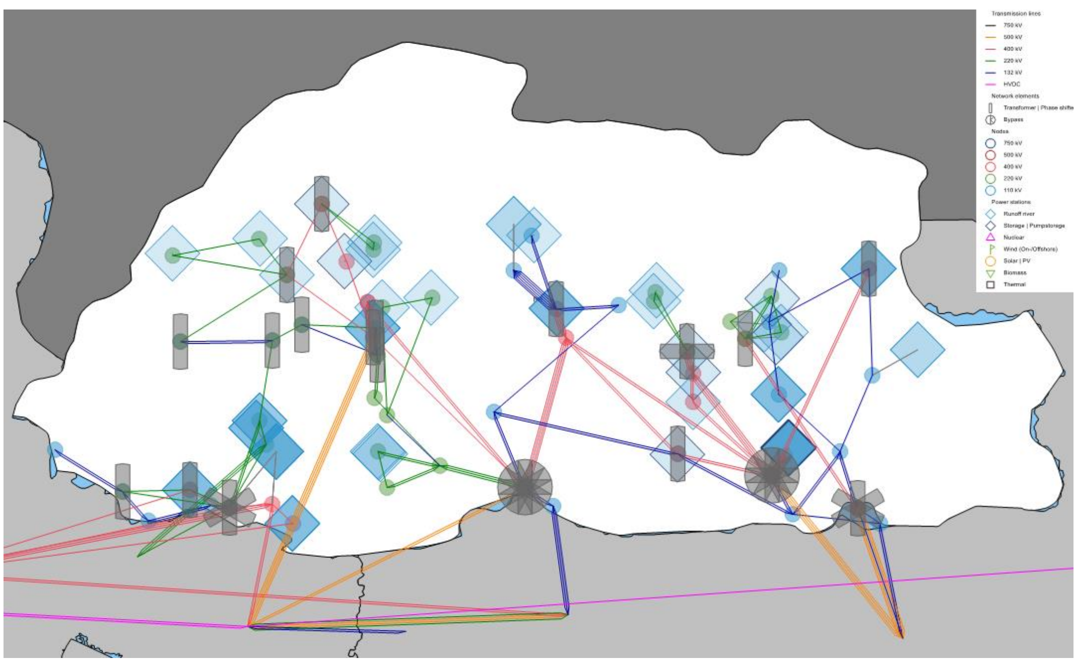


Figure (39) Visualization of the transmission network of Bhutan Region

h. Nepal (NP)

The region of NP, similar to the BH region is also important to the sustainability of the Indian power sector considering the available of a huge untapped hydro potential in the nation. However, the country also is battling with energy access due to shortage of transmission capacity, thus making the overall development of the regional grid a major priority. The present-day grid in the NP region is also concentrated in the south, with a 132 kV transmission connecting the major populated regions from West to East.

With the proposed ‘electrical highway’, a 220 kV transmission project reinforcing the existing 132 kV grid and connecting several planned hydro power installations, the NP region is set to observe a large change in their electricity system. Several dam hydro and pumped storage facilities are also planned in the region by the GoI, thus making the development of the electricity sector of the NP region interesting for the Indian power sector. From the Figure (40), it can be observed that a network of 132 kV and 220 kV lines form the Nepalese grid, and cross border interconnections to the Indian regions in the 400 kV voltage levels have been proposed for the coming decade. The effective transfer of electrical power to the Indian regions could be the factor promoting economic and social welfare in the region, generating incomes and assuring energy security. Most of the hydro power investments planned by India in the region will be operated on an 80-20 scale, with 80 percent of the electricity generated imported to India, while 20 percent being available for Nepal. A visual representation of the Nepalese power grid is as shown in the Figure (40) below.

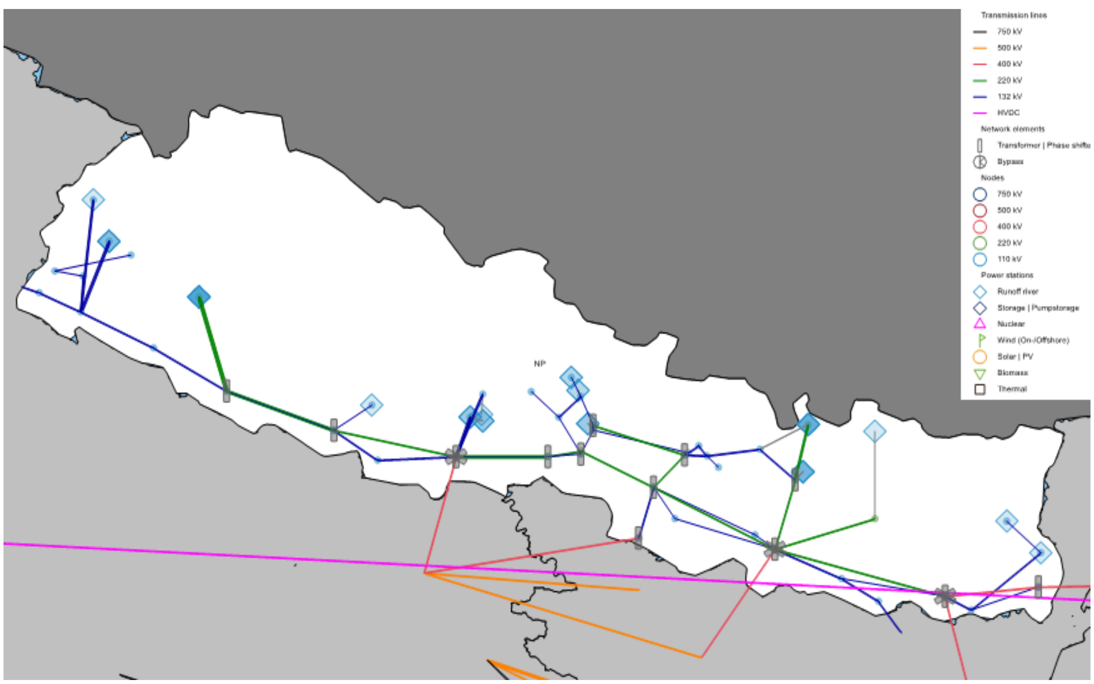


Figure (40) Visualization of the transmission network of Nepal Region

i. Sri Lanka (SL)

The region of SL is a unique island power system, which has managed to sustain its electricity needs majorly from gas-fired, hydro and oil-fired generation capacities. All peak loads at the demand centers are met through the use of generating stations on oil barges/ containers, located near the demand center. Colombo, the capital city of the country is the most populated and the city with the highest demand, and several barges with large diesel generators are used to satisfy peak load.

The existing transmission grid in the region operates on 132 kV voltage level with a small 220 kV network reinforcing the demand centers in the west of the region. Several new 220 kV infrastructure is proposed and many already under construction, with the increase of generating capacities in the north western and northern part of the region. The first HVDC cross border transmission line is expected to be operational in 2023, is expected to open up many possibilities for the SL region with effective imports from the SR region. Also, plans for the installation of a nuclear power station in the eastern shore of the country is being proposed, with India and Russia supporting the investment and acquisition of the generating technology. A few 400 kV lines are also proposed to support the planned nuclear capacity, along with the RES expansion in the south. A visual representation of Sri Lankan Grid is as shown in the Figure (41) below.

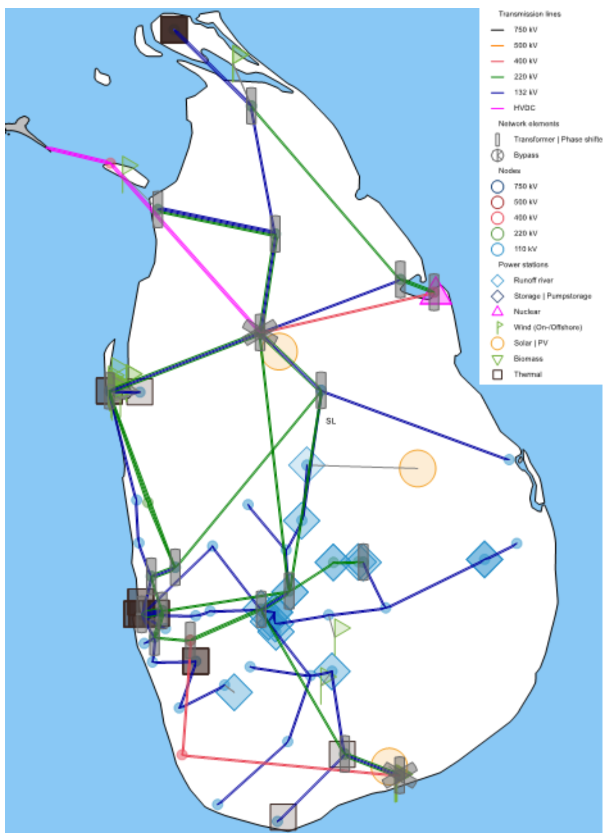


Figure (41) Visualization of the transmission network of Sri Lanka Region

3.3.4. Net Transfer Capacities

The Net Transfer Capacity (NTC) is a significant parameter which sets a limit for the transfer of electricity between power regions, and is based on the available transmission capacities between the regions. NTCs are usually described in most cases by the power carrying capacity of the inter-regional cross border transmission lines (which are already described with unique transmission line IDs in the 'Tbl_Stamm_Leitungen').

However, for market model simulations, the defining of NTCs between two power regions as separate inputs to the model becomes significantly important. This increases the ease to set the limit or restriction to the cross-border trade and while forming the basis of the Zonal Pricing (ZP) model mechanism. The NTC values defined are used in calculating the net import and export in a particular region and forms the basis for the electricity price in that region. The NTC values which restrict the transfer/ trade of electricity between the regions, are defined between the different simulation regions in the 'Tbl_Stamm_NTC'. These 9X9 NTC matrices are defined for each simulation year, with respect to already available trading information or proposed improvements by government reports. A brief representation of the NTC values in the base year 2006 is as described in the table below. With the addition of each cross-border transmission line, and published values, the NTC values are to be increased between the respective regions, hence an evolution of the NTC values also forms and important input parameter.

2006	NE	BA	BH	ER	NP	NR	SL	SR	WR
NE		1000	50	1250	0	0	0	0	0
BA	1000		0	0	0	0	0	0	0
BH	50	0		0	0	0	0	0	0
ER	1250	0	0		125	3430	0	3100	1790
NP	0	0	0	125		0	0	0	0
NR	0	0	0	3430	0		0	0	2100
SL	0	0	0	0	0	0		0	0
SR	0	0	0	3100	0	0	0		1720
WR	0	0	0	1790	0	2100	0	1720	

Table (2) Example for NTC matrix definition in ATLANTIS_India for the year 2006

3.3.5. The Power plant fleet

A power plant is a generating station which feeds in electrical energy to a specific node, to be transported across a transmission line connected to this 'feed in' node to a demand center. Normally, power plants are defined as close to the demand centers as possible, as is the actual case with many coal-fired and gas-fired capacities in India. However, with certain renewable energy technology types like hydro power, solar PV and wind energy, the power plants are geographically located where the resource availability is optimum. When this is the case, such a geographically dependent power plant feeds in to a specific node with minimum demand weightage, defined specifically for the power plant feed in. A node which is already defined near the power plant already connected to the transmission network could also be defined as feed in points for the power plant, and care is taken that the power plant feeds in electrical power at the lowest possible voltage level in the node. The power plants are defined as input data to the simulation model by defining the excel table 'Tbl_Stamm_Kraftwerke'.

The power plants are classified by their specific generation technology types, fuel types used, model region, investing company, and starting years. The end of use year of the power plant, when data is not available, is assumed based on the assumption that the power plant operates throughout its technical useful life time. This gives us a realistic simulation of the real case as most power plants with long lifetimes usually end up operating more than their economic life times mentioned in the accounting books of the owner company. Also, a unique ID differentiating the power plant by its technology type and region is to be defined to identify each of the defined power plant. The ID is also coupled with the unique node ID, where the designated feed in points to the electrical grid are defined. The amount of expected annual electricity yield, in relation with the operational full load hours and monthly generation factors are also defined for the power plant addition. This gives an almost realistic quantification of the annual generation of electrical energy by the specific power plant. The generation of the power plant is also distributed on a monthly basis, by defining the monthly generation factors, to give an estimation of the average power plant usage in different months in the year. Weather-dependent generation technologies like run of river hydro, solar PV and wind power need specific monthly generation factors, based on the existing seasonal variations within each region. This helps in giving an accurate and a realistic estimation of the generation by the RES capacities, whose availability significantly varies with each model region and season. A visual representation of the power plants in the model is as shown in the Figure (42).

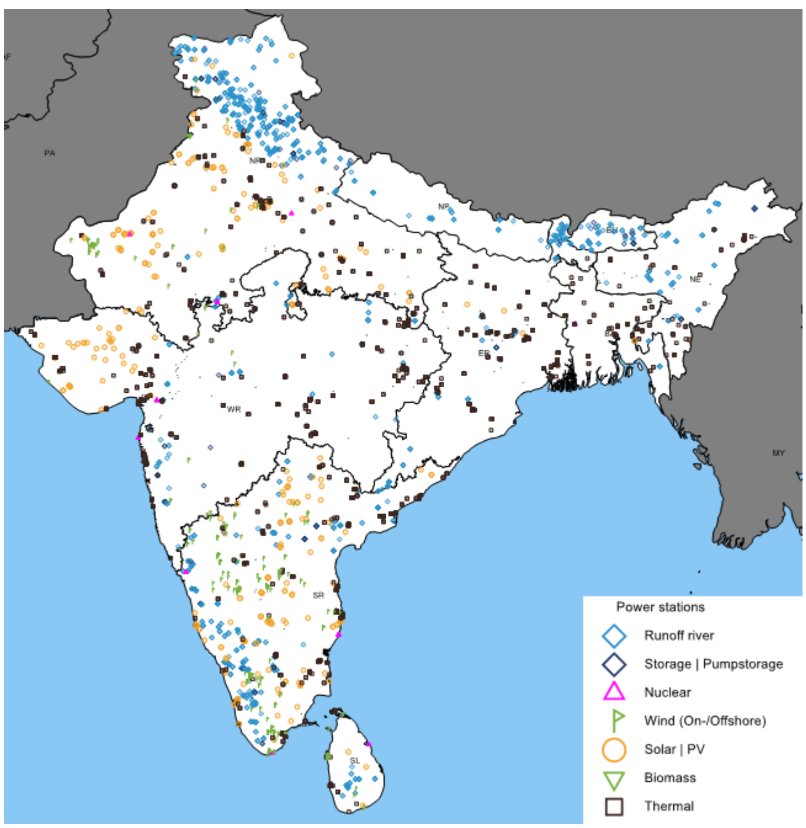


Figure (42) A visual representation of the Power plants in the Indian Subcontinent region, ATLANTIS_India

3.3.5.1. Power plant definition

As discussed, the definition of a power plant in the ATLANTIS_India input data is done by defining several common parameters like power plant type, fuel type, efficiency values, start-up year, feed in nodes, model region, generation factor, overall expected energy yield, geographical locations, and several other parameters indicating if the powerplant is supply dependent, industrial CHP or must run power plants. Each generating unit in large power plants complexes have been given a unique identification name making it easier to differentiate similar power plants in the region. The input data, like every other input data, is also prepared as tables in Microsoft excel. The following section gives a detailed classification of the definition of generation technology types used in ATLANTIS_India.

3.3.5.2. Power plant cost structures

The price of electricity generation and the capital stock offered by a particular capacity of power plant technology type depends on its cost structure. Hence, the definition of the cost structure in the model is really important. The cost structure makes it possible to bring in an economic dimension to the simulation model. In ATLANTIS_India, all plant types defined have a generalized cost structure, particular to each technology type, for the sake of simplicity. In some cases, due to the unavailability of reliable actual data, the actual available European data (EUROSTAT) (v) on the cost structure of the power plant types have been used and scaled down to the Indian values. The scaling down is done, based on a factor derived by comparing the purchasing power parity (PPP) of India with the average PPP value in specific countries of the EU (w). Additionally, the historical currency exchange/conversion values from Indian Rupees (₹) to the European Euro (€) were subsequently used, from various open source historical currency conversion websites.

However, accuracy has been given prominence over simplicity, and hence actual values for Indian power plants were rigorously sought after and an average value of specific costs for several technology types included in the model has been used. The following is a brief discussion of the different cost structures and economic parameters included in the economic simulation calculations. The values are represented in Euros (€), and the timeline of exchange rates are also considered. The inflation rates, interest rates, land values et cetera are also studied for a better understanding and definition of the power plant cost structure. Technology specific data was found only for India, and the cost structures for the regions BA, BH, NP and SL were calculated based on the PPP comparisons.

a. Coal power plants (Bituminous brown coal and lignite)

Coal-fired generating technology has been in the market for such a long period of time that the international trade for the fuel and technology have similar cost structures in most of the coal dominant countries (ex. China, Poland, India). The most expensive component of the cost structure being the boiler and the turbine costs (capital) and variable costs like fuel costs, most of coal-fired generation capacities have similar structures. Average prices for each section of a coal power plant is as shown in the accompanying Table (3).

Particulars	**₹**	**€**
Plant Capacity	660 MW	
Capital Cost	60000000/MW	800000/ MW
Debt Equity Ratio	70:30	
Return on Equity	15,50%	
Interest on Loan	10%	
Working Capital	3960000000 (10%)	52800000
Interest on Working capital	10%	
Rate of Depreciation	5.28%	
O&M Cost	14.62%	
Plant Load factor	85%	
Plant Availability Factor	85%	

Particulars	**₹**	**€**
Specific Oil Consumption	1 ml /kwh	
Price of Oil	35000/kl	466.67/ kL
GCV of oil	10000 kCal/l	
Station heat rate	2425 kCal/kg	
Cost of Coal	2000/ tonnes	30/ tonnes
Auxiliary power consumption	6.50%	
Plant Life	25 years	
GCV of coal	3800 kcal/kg	

Table (3) Average prices in the cost structure definition of coal power plants in ATLANTIS_India [*Source: (x)(y)*]

An overall cost estimation was also done, based on different coal types and their respective prices in India, and the cost structure of coal-fired generation capacities used in this model is as shown in the Table (4) below.

Technology type	**₹ / MW**	**€/ MW**	**Capital Cost, €**	**Capacity, MW**
Domestic Coal (Brown coal)	40000000	533333.333	352000000	660
Lignite	40000000	533333.333	533333333	1000
Imported Coal (Bituminous)	42000000	560000	560000000	1000

Table (4) Overall cost structure of coal-fired power plants in ATLANTIS_India [*Source: (z)*]

The data confirms the fact that power from coal fired capacities are the least expensive, compared to the other generating technology types in the sub-continent region.

b. Nuclear Power

Nuclear power, as discussed before has always been an interesting topic in the region. Since nuclear power plants are considered strategic assets of the country, there is a lot of confidentiality over the data on nuclear power plants in India. Thus, the available data of one power station was taken and used for all the other generating stations. However, comparison between capital cost of several types of nuclear power technology types were also considered and scaled appropriately. The accompanying Table (5) gives a brief estimation of the cost structure of nuclear power plants used in ATLANTIS_India.

Particulars	**Indian rupees (₹)**	**€**
Sum of annual construction costs	18160000000	242133333
Capacity	440 MW	440 MW
Auxiliary consumption	12%	12%
Economic lifetime	40 years	40 years
Uranium fuel price	16450 /kg	219.333/ kg
Initial Uranium loading	111.6 tonnes	111.6 tonnes
Uranium consumption	2.05E-05 kg/kwh	2.05E-05 kg/kwh
Heavy water price	24880 / kg	331.733/ kg
Initial heavy water loading	420 tonnes	420 tonnes
Heavy water losses	14000 kg/ year	14000 kg/ year
Transport of spent fuel	878 / kg	11.707/ kg
Decommissioning cost	10% of capital cost	10% of capital cost
Operation and Maintenance	2% of the capital cost	2% of the capital cost

Table (5) Average cost structure of a nuclear power plant in ATLANTIS_India [*Source: [3](z)*]

The definition of the cost structure for the new HT-FBR Thorium reactor based nuclear power plants are assumed to be similar, if not more expensive than the EPR based nuclear power plants in Europe. The data was eventually scaled down with respect to the PPP comparison of India with the EU.

c. Hydro power plants

The cost structure of a hydro power plant is normally dependent on the installed capacity (component selection) and the geographical conditions. However, in the scope of this thesis, the distinction of the hydro power plants is solely made on the size of the capacity. All the small hydro and run of river hydro power plants are assumed to be constructed on a single category of rivers defined. The size category of the hydro power plants can be classified in to four groups: 'Small Scale 1', 'Small Scale 2', 'Large Scale 1' and 'Large Scale 2'. When specific costs on hydro power plants are available, they are taken into consideration, and with the capacity classifications the average costs are calculated. These calculated values are as shown in the accompanying Table (6).

Classification in ATLANTIS_India	Capital Cost	Capacity (kW)	€/kW
Small Hydro	Small Scale 1	< 2500	1456.953642
Run of River Hydro	Small Scale 2	24000	993.3774834
	Large Scale 1	100000	496.6887417
Dam Hydro	Large Scale 2	> 1000000	2483.443709
	O&M	**Capacity**	**€/kW/year**
Small Hydro	Small Scale 1	< 2500	26.49006623
Run of River Hydro	Small Scale 2	24000	19.86754967
	Large Scale 1	100000	29.8013245
Dam Hydro	Large Scale 2	> 1000000	29.8013245

Table (6) Average prices in the cost structure definition of Hydro power plants in ATLANTIS_India [*Source: IRENA, (aa)*]

The assumptions were found to be reasonable when compared with the published results (IRENA) (u)(aa). Since a majority share of the installed hydro power capacity is owned by companies of the central government, land rent and other costs were not really taken in to account, limited to a minimum value.

d. Gas- and oil-fired power plants

With both technology types having lower capital costs and higher variable costs, the cost structures of natural gas and oil power plants are found to be quite similar. Hence for the sake of simplicity, but with accuracy in mind, an average cost structure has been designed for such power plant types. The fuel costs are differentiated in the definition of fuel types used in the model. The Table (7) gives a brief representation of the cost structure of the natural gas, diesel and naptha power plants.

Capital Cost estimates	₹/ MW	€/ MW	Capital Cost	Capacity (MW)
LNG	27000000	360000	90000000	250
Naptha	27000000	360000	36000000	100
Gas	27000000	360000	90000000	250
Diesel	35000000	466666.667	116666667	250

Table (7) Average prices in the cost structure definition of gas-fired and oil-fired power plants in ATLANTIS_India [*Source: [3](x)(y)*]

Diesel based power plants are usually used as auxiliary power plants for covering industry peaks, also normally used as peak load smaller capacities. But with larger capacities, the initial investment per MW increases almost linearly with the increase in the size of the installed capacity.

e. Wind power plants

Wind power plant components are usually imported either from Europe or China, so based on the global published technology learning curves, the costs are to be estimated. However, most of the wind power plants in the country are planned and constructed in rural and remote areas. This common factor with all the wind power plants in the country allows for approximation of the land costs and several other plant-specific costs. Based on a study of the evolution of wind power in India (CERC), the capital cost and the component cost structure for a typical wind power plant built in India is as shown in the accompanying Table (8).

Particulars	₹/ MW	€/MW
Capital cost	68500000	913334
Plant and Machinery	90%	822000
Land Cost	2%	18266
Evacuation Charges	6%	54800
Preliminary Expenses	2%	18199

Table (8) Average prices in the cost structure definition of wind power plants in ATLANTIS_India [*Source: CERC, (bb)*]

Since most of the RES power plants in India have been subsidized and financed by governmental regulators and organizations, it is important to also consider the economic parameters defining the financing of wind power plants in India. The Table (9) below describes the financial structure offered by the GoI to a wind power plant investor.

Particulars	Debt	Equity
	433.86	185.94
Return on equity	20%	
Interest on loan	10%	9,85%
Depreciation	5.83%	1.54%
O&M fixed	1 Month	
Maintenance	15% of Operating Expenses	
Interest on working capital	13.26%	

Table (9) Economic parameters defining the cost structure of wind power plants in ATLANTIS_India, [*Source: CERC*]

f. Solar PV Power Plants

Solar PV technology currently is the most subsidized and promoted generation technology type right in India. Hence large capacities of solar PV have been subsequently added to the Indian power plant fleet in the recent few years. The cost structure of this technology type has to be studied in detail, as the installed capacities can be found almost any region of the country: urban, rural and waste lands. The following cost structure, based on a governmental report by the CEA GoI, India is as shown in the Table (10).

Components	₹ Lakhs/ MW	€/MW
Land	25	33334
Module	330	440000
Civil and general works	55	73334
Mounting Structures	40	53334
Inverters	40	53334
Electricals	65	86666.6667

Components	₹ Lakhs/ MW	€/MW
Grid Extension and bay extension	40	53334
preliminary expenses: Approvals, land leveling	15	20000
Total Capital Investment	610	813334
O&M	6	8000
Escalation (annual)	5%	66.67
Insurance	0.15%	2
Escalation (annual)	0%	0

Table (10) Average component cost for solar PV in ATLANTIS_India (1 Lakh =100000) [*Source: (bb)(cc)*]

With the increase in demand for solar components resulting from the increasing added capacity, the consistent decrease in the capital cost was observed. This has been taken into the account when calculating cost projections over the years (cost learning curves).

Year	Capital Cost (₹ lakhs/MW)	€/MW
2010-11	1700	2266667
2011-12	1442	1922667
2012-12	1000	1333334
2013-14	800	1066667
2014-15	691	921334
2015-16	605,85	807800

Table (11) Cost of solar PV technology over the years, (1 Lakh =100000) [*Source: CERC, (bb)*]

By the year 2019, the LCoEg by solar PV is expected to fall well below the cost of electricity from imported coal [23], and has been estimated to compete with wind energy which is currently one of the cheapest RE technology type in the country. The observed capital cost decrease is as described by the Table (11) accompanied.

3.3.5.3. Conversion efficiency

The operation of a power plant inevitably leads to wear and tear of the power plant components, resulting in more fuel needed to produce the same amount of electricity as before. The efficiency of a power plant deteriorates over the service life time and the offering price of electricity from the power plant increases accordingly. The degradation of efficiency of the power generating components is also taken in to account in the model. This is based on a factor calculated considering the startup and the shutdown years of the power plant. The factors are as shown in the Table (12) below, and the efficiency in each year is calculated by the given equation (E1).

Technology type	**Startup year**	**End year**	**a**	**b**	**c**
Gas_GT, Oil	-	2015	24.1675	0.16879	1.00
	2016	-	24.1675	0.16879	1.00
Gas_CC, Oil_CC	-	2015	28.5065	0.5028	1.00
	2016	-	61.1885	0.1089	1.00
Bituminous, IGCC	-	1964	19.8309	0.9011	1.00
	1965	1993	30.96	0.1638	1.00
	1994	2015	18.8555	0.4394	1.00
	2016	-	47.4165	0.2167	1.00
Biomass, Biogas	-	1964	19.8309	0.9011	0.90
	1965	1993	30.96	0.1638	0.90
	1994	2015	18.8555	0.4394	0.90
	2016	-	47.4165	0.2167	0.90
Lignite	-	1964	19.8309	0.9011	0.96
	1965	1993	30.96	0.1638	0.96
	1994	2015	18.8555	0.4394	0.96
	2016	-	47.4165	0.2167	0.96
Gas, Oil	-	1964	19.8309	0.9011	1.045
	1965	1993	30.96	0.1638	1.045
	1994	2015	18.8555	0.4394	1.045
	2016	-	47.4165	0.2167	1.045

Table (12) Conversion efficiencies defined for specific technology power plant types in ATLANTIS_India

Efficiency calculation equation:

$$\eta_{year_{startup}} = \frac{(a+b\cdot(Year_{startup}-1950)}{100}\cdot c \qquad \text{(E1)}$$

Where

$\eta_{year_{startup}}$ Efficiency in the startup year

a, b, c Factors (as mentioned in the table)

$Year_{startup}$ Startup year of the power plant

Some types of power plant have a fixed pre-determined efficiency in the model. These technology types are described in the Table (13) given.

Technologies	Startup year	End year	Efficiency
Geothermal Photovoltaic, Solar Thermal Run of River hydro, Dam hydro Wind, Wind_OffShore Others, Import	-	-	1.00
Erdgas_IC, Oil_IC	-	-	0.40
Nuc_BWR, Nuc_Candu	-	-	0.33
Nuc_EPR, Nuc_Th_FBR	-	-	0.35
Pumped storage powerplants	-	2005	0.72
	2006	2015	0.74
	2016	-	0.75

Table (13) Fixed efficiency values for certain power plant technology types in ATLANTIS_India

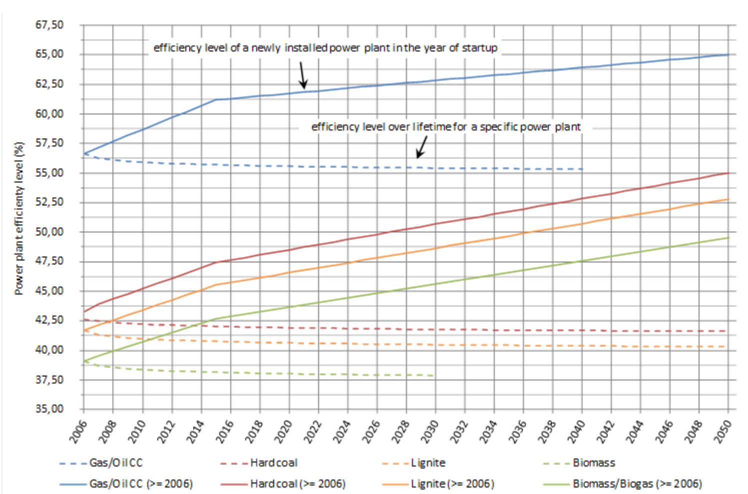


Figure (43) Development of the efficiency improvement of selected power plant technologies

Also, the projection of the efficiencies of newly built power plants (solid lines), as well as the change of these efficiencies over the service life (dotted lines) are for some selected power plant types are as shown in the Figure (43). The decrease of efficiency due to service is assumed to be gradual, as power plants in the sub-continent region are relatively new.

3.3.5.4. Technology learning curves

The calculation of the acquisition costs for power plant technology in the model is based on so-called learning curves. The basis for this is a report by the Department or Energy (USA) (ff), which published relevant publications on this topic. Learning curves describe a cost reduction of different technologies caused by the cumulative technical progress. Each technology passes through different stages of development (new / revolutionary, advanced / evolutionary, mature), which in turn are subject to different learning factors.

Learning factors describe the cost reduction (in percentages of acquisition cost) caused by a doubling of the installed capacity of a technology - for example: a 10 percent learning factor means a cost reduction of 10 percent (the original cost per MW) with a doubling of the installed power plant capacity. However, the definition of breaks between the specific individual stages of development of a technology is problematic. This must be estimated as well as future learning factors. Figure (44) shows the evolution over time of the cost of some selected technologies. For photovoltaics, the different development periods (1-3) are additionally shown on the basis of regression lines.

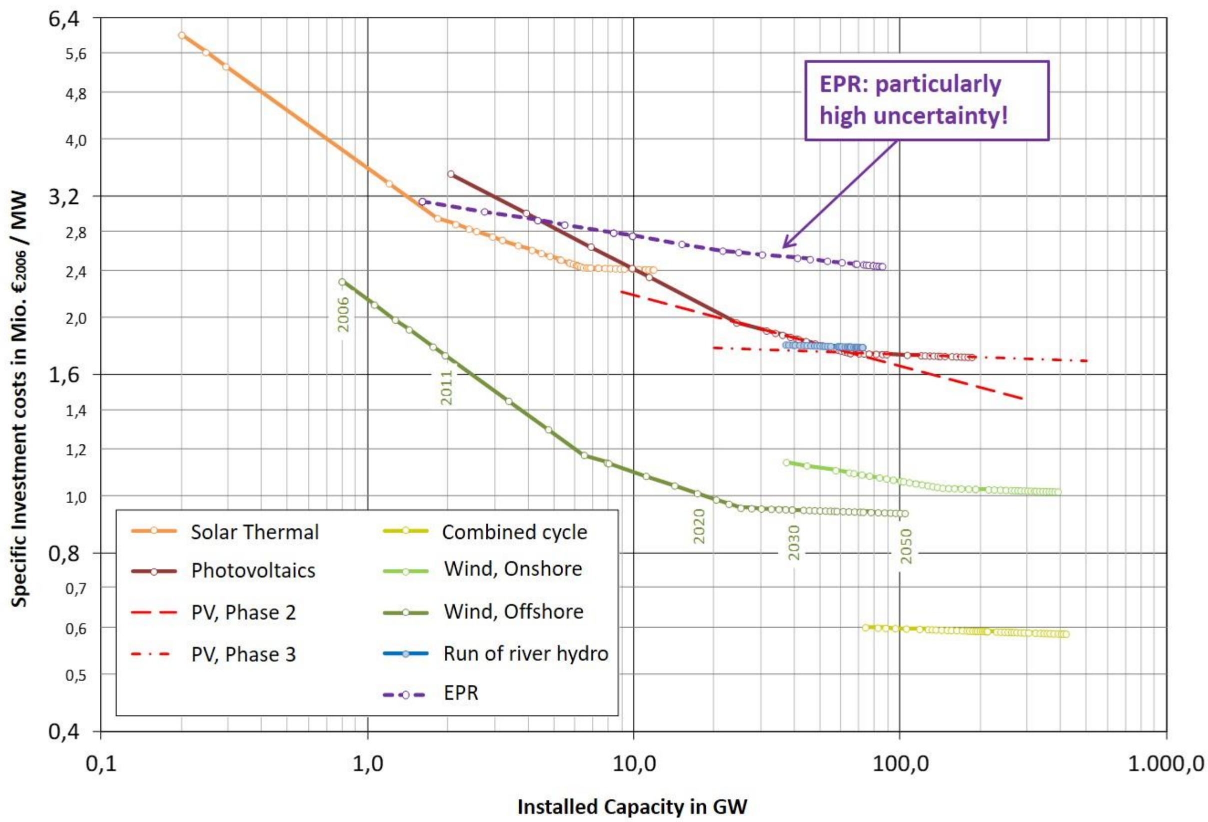


Figure (44) Learning curves of specific investment costs of power plant technology type [*Source: IEE, TUG*]

When calculating the final construction cost of a power plant, additional parameters such as gross power capacity or a construction cost index for the start-up year must also be considered. In addition, there is a corresponding cost reduction parameter for revitalized power plants (refurbishment / re-powering), after which usually only a mechanical / electro-technical upgrade of the power plants takes place. The learning curves and factors for the specific technology types used in the model are as described in the Table (14).

However, these calculated assumptions are made with many uncertainties and must be further evaluated with caution. Thus, comparisons with available empirical values are absolutely necessary for the accurate representation of the economic scenarios.

Power Plant Technologies	Cost per MW Phase 1	P installed Phase 1	Pmax Phase 1-Phase 2	Pmax Phase 2-Phase 3	Learn-factor Phase 1	Learn-factor Phase 2	Learn-factor Phase 3
Lignite coal	1200000	63583	1	1	1	1	1
Gas	1000000	19509	1	1	1	1	1
Gas_CC	600000	73881	1	1	1	1	1
Gas_GT	400000	16722	1	1	1	1	1
CCGT	1410000	1184	1	1	1	1	1
Run-of-River Hydro	1800000	38076	1	1	1	1	1
Nuclear_BWR	2000000	9519	1	1	1	1	1
Nuclear_CANDU	2000000	655	1	1	1	1	1
Nuclear_EPR	3000000	3000	8	32	5	3	1
Nuclear_Th_FBR	3000000	1200	8	32	5	3	1
Nuclear_PWR	1800000	102617	1	1	1	1	1
Oil	1000000	30636	1	1	1	1	1
Oil_CC	600000	85531	1	1	1	1	1
Oil_GT	400000	4331	1	1	1	1	1
Oil_IC	710000	1798	8	32	5	5	1
Solar PV	3500000	2048	8	32	15	8	1
Pumped hydro	3100000	39387	1	1	1	1	1
Solar Thermal	2980000	200	8	32	20	10	1
Others	2000000	43	1	1	1	1	1
Dam hydro	3000000	55892	1	1	1	1	1
Hard / Bituminous coal	1100000	87370	1	1	1	1	1
Wind Onshore	1140000	37248	4	6	5	5	1
Wind Offshore	2300000	100	1	1	20	10	1

Table (14) Acquisition costs and learning curve factors: power plant technology types at a glance

3.3.5.5. Definition of fuel types and emission intensities

Definition of fuel types for each region brings in more accuracy of the resulting economic simulations, as there are significant price differences in each type of fuel used to generate electricity, in the sub-continent region. A brief overlook on the prices of, and their specific emission intensities can be seen in the Table (16) and a price evolution can be seen in the Figure (45). The EU values (Table (15)) or higher-end values for specific carbon intensities for each fuel type has been considered, for the sake of simplicity in defining the fuel type. The 2006 prices for fuel is based on specific data collected and valid assumption based on several studies [3][28][43][45](d)(v) (w).

Fuel type	**Fuel ID**	**Region**	**Units**	**Specific Carbon intensities**	**Price 2006**
Biomass	EUBIOMASSE	EU	€/MWh	0	6.923760891
Lignite coal	EUBRAUNKOH	EU	€/MWh	0.400000006	7
CO2 model pricing	EUCO2_____	EU	€/MWh	0	17.87800026
Natural Gas	EUERDGAS__	EU	€/MWh	0.202000007	21.90415955
Import price	EUIMPORT__	EU	€/MWh	0	2
Run of River Hydro	EULAUFWASS	EU	€/MWh	0	0
Solar	EUSONNE___	EU	€/MWh	0	0
Pumped Hydro	EUSPKWWASS	EU	€/MWh	0	0
Nuclear	EUURAN____	EU	€/MWh	0	1.62438977
Wind	EUWIND____	EU	€/MWh	0	0
Bituminous coal	EUSTEINKOH	EU	€/MWh	0.352736477	8.930641833

Table (15) Reference values from the EU energy economics for the definition of fuel scenarios

Fuel type	**Fuel ID**	**Region**	**Units**	**Specific Carbon intensities**	**Price 2006**
Lignite Coal	NEBRAUNKOH	NE	€/MWh	0.400000006	2.03
Natural Gas	NEERDGAS__	NE	€/MWh	0.202000007	3.992275629
Oil (Diesel)	NEHEIZOELL	NE	€/MWh	3.904982374	1.549219123
Heavy Oil	NEHEIZOELS	NE	€/MWh	3.904982374	1.549219123
Clean Coal technology	NELIGFIER_	NE	€/MWh	0.045808861	2.03
Bituminous coal	NESTEINKOH	NE	€/MWh	0.352736477	1.955810562
Natural Gas	NRERDGAS__	NR	€/MWh	0.202000007	7.984551259

Fuel type	Fuel ID	Region	Units	Specific Carbon intensities	Price 2006
Oil (Diesel)	NRHEIZOELL	NR	€/MWh	3.904982374	3.645221467
Heavy Oil	NRHEIZOELS	NR	€/MWh	3.904982374	3.645221467
Clean Coal technology	NRLIGFIER_	NR	€/MWh	0.045808861	1.955810562
Bituminous coal	NRSTEINKOH	NR	€/MWh	0.352736477	1.955810562
Natural Gas	WRERDGAS__	WR	€/MWh	0.202000007	7.984551259
Oil (Diesel)	WRHEIZOELL	WR	€/MWh	3.904982374	3.645221467
Heavy Oil	WRHEIZOELS	WR	€/MWh	3.904982374	3.645221467
Clean Coal technology	WRLIGFIER_	WR	€/MWh	0.045808861	1.955810562
Bituminous coal	WRSTEINKOH	WR	€/MWh	0.352736477	1.955810562
Natural Gas	SRERDGAS__	SR	€/MWh	0.202000007	7.984551259
Oil (Diesel)	SRHEIZOELL	SR	€/MWh	3.904982374	3.645221467
Heavy Oil	SRHEIZOELS	SR	€/MWh	3.904982374	3.645221467
Clean Coal technology	SRLIGFIER_	SR	€/MWh	0.045808861	1.955810562
Bituminous coal	SRSTEINKOH	SR	€/MWh	0.352736477	1.955810562
Natural Gas	ERERDGAS__	ER	€/MWh	0.202000007	7.984551259
Oil (Diesel)	ERHEIZOELL	ER	€/MWh	3.904982374	3.645221467
Heavy Oil	ERHEIZOELS	ER	€/MWh	3.904982374	3.645221467
Clean Coal technology	ERLIGFIER_	ER	€/MWh	0.045808861	1.955810562
Bituminous coal	ERSTEINKOH	ER	€/MWh	0.352736477	1.955810562
Natural Gas	BAERDGAS__	BA	€/MWh	0.202000007	3.992275629
Oil (Diesel)	BAHEIZOELL	BA	€/MWh	3.904982374	4.009743614
Heavy Oil	BAHEIZOELS	BA	€/MWh	3.904982374	4.009743614
Clean Coal technology	BALIGFIER_	BA	€/MWh	0.045808861	3.43
Bituminous coal	BASTEINKOH	BA	€/MWh	0.352736477	2.589886132
Natural Gas	BHERDGAS__	BA	€/MWh	0.202000007	11.97682689
Oil (Diesel)	BHHEIZOELL	BA	€/MWh	3.904982374	4.009743614
Fuel type	**Fuel ID**	**Region**	**Units**	**Specific Carbon intensities**	**Price 2006**

Heavy Oil	BHHEIZOELS	BA	€/MWh	3.904982374	4.09743614
Clean Coal technology	BHLIGFIER_	BH	€/MWh	0.045808861	3.01
Bituminous coal	BHSTEINKOH	BH	€/MWh	0.352736477	2.643469983
Natural Gas	NPERDGAS__	NP	€/MWh	0.202000007	7.984551259
Oil (Diesel)	NPHEIZOELL	NP	€/MWh	3.904982374	4.009743614
Heavy Oil	NPHEIZOELS	NP	€/MWh	3.904982374	4.009743614
Clean Coal technology	NPLIGFIER_	NP	€/MWh	0.045808861	3.01
Bituminous coal	NPSTEINKOH	NP	€/MWh	0.352736477	2.643469983
Natural Gas	SLERDGAS__	SL	€/MWh	0.202000007	11.97682689
Oil (Diesel)	SLHEIZOELL	SL	€/MWh	3.904982374	1.549219123
Heavy Oil	SLHEIZOELS	SL	€/MWh	3.904982374	1.549219123
Clean Coal technology	SLLIGFIER_	SL	€/MWh	0.045808861	2.73
Bituminous coal	SLSTEINKOH	SL	€/MWh	0.352736477	2.464857146

Table (16) Prices of fuel defined for specific model regions, including values of their specific carbon intensity values [*Source: (v)(w)*]

The clean coal technologies implemented in specific regions are basically defined as coal fired capacities with higher efficiencies and by defining a new type of fuel in the input data. Furthermore, all the oil-fired power plants in the model regions are assumed to be run with diesel oil (light oil), with both fuel types being more than usually expensive and with large carbon intensities.

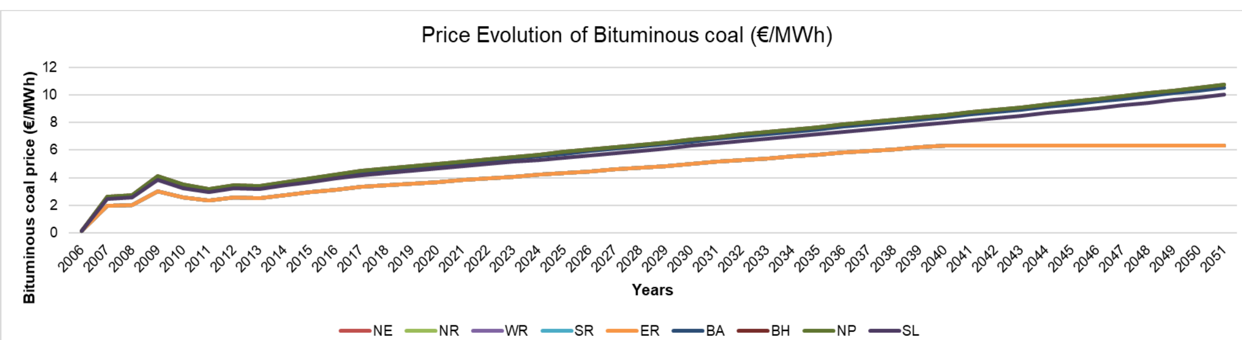


Figure (45) Comparison of fuel price of bituminous coal in different model regions, as an example for evolution of fuel prices

The CO_2 prices resulting from the emissions from electricity generation in the conventional power plant fleet have not been considered in the course of this thesis, as India has no centralized CO_2 pricing mechanisms like in the EU (ETS) implemented in the power sector yet. However, a provision for defining the CO_2 prices if and when a pricing mechanism is introduced as been provided in ATLANTIS_India, for future works. The projection of fuel prices is also specific to each model region, along with the prices for each fuel type. A linear projection of the price development in each region gives a complete definition of the fuel prices situation in the model. The development of the fuel prices is assumed to saturate after reaching a specific cap defined in accordance to several assumptions taken as a part of the study. An example for the price evolution of bituminous coal in the model is as shown in the Figure (45).

3.3.5.6. Monthly generation factors

It can be very complex to define the resource availability for weather-dependent (supply dependent) power plant technologies. However, the overall seasonal variations and the expected energy yield in a year can be defined to set a pattern for generation from weather dependent technology types like VRE and run of river hydro power plants. Based on available weather and seasonal resource data, monthly generation factors were defined for each specific type of weather-dependent power plant technology, and the expected energy yield was calculated based on the average operational hours observed in the model region associated with the specific power plant. These generation factors are basically normalized weightages for electricity generation in the specific powerplant, and the amount of energy generated each month is dependent on the defined generation factor. The Figure (46) gives an overall representation of generation factors calculated for each region in ATLANTIS_India, for Solar PV, Wind (Onshore and Offshore), and run-of-river hydro power plant capacities.

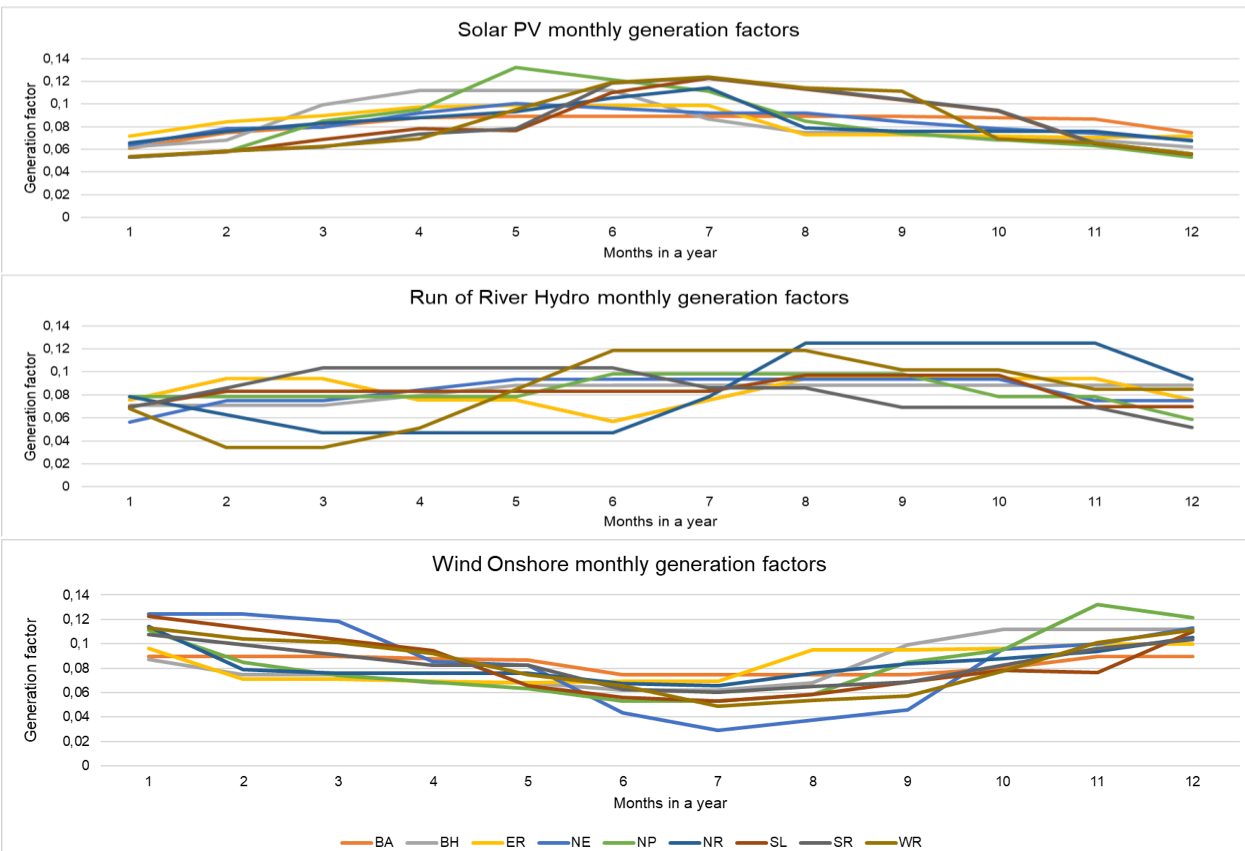


Figure (46) Generation factors defined for solar PV, run of river hydro, wind-onshore and -offshore power plant capacities in specific regions

The annual expected energy yield values for these power plant capacities are based on the number of full load hours estimated in average in the geographical region of each specific model region for each power plant type. This gives us a simplistic calculation of the generation from such weather dependent power plants.

3.3.6. Electricity demand distribution

The electricity demand distribution in the model is node- specific. This means that each node defined in the physical model accounts for a weightage value, which distributes the overall electricity demand and the additional demand of the specific region accordingly based on several parameters. The major electrical demand sectors in the India are the Domestic, the Industrial and services, and the Agricultural sectors [3]. In ATLANTIS_India, the demand distribution is carefully done after considering the concentration of industrial, residential and agricultural areas in the country. The three areas are targeted as demand distribution factors, as they account for almost over 80 percent of the overall electricity demand in the country. A visual representation to identify the concentration of these areas and their specific nodes are as shown in the Figures (47) (48) and (49)

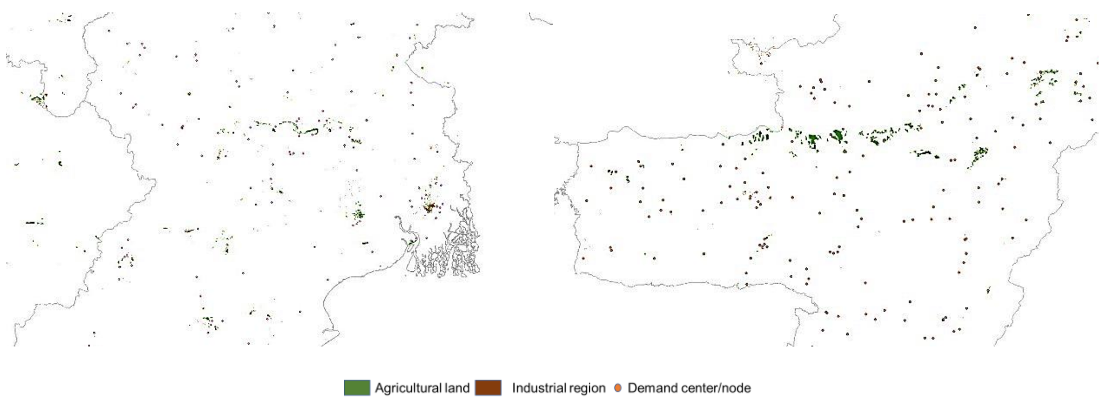


Figure (47) Representation of identification of weightages of demand centers in the ER (left) and NE (right) regions

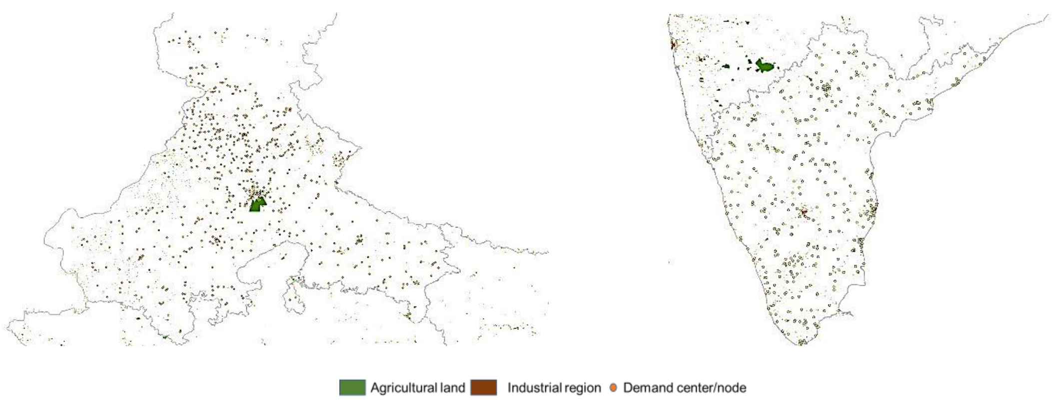


Figure (48) Representation of identification of weightages of demand centers in the NR (left) and SR (right) regions

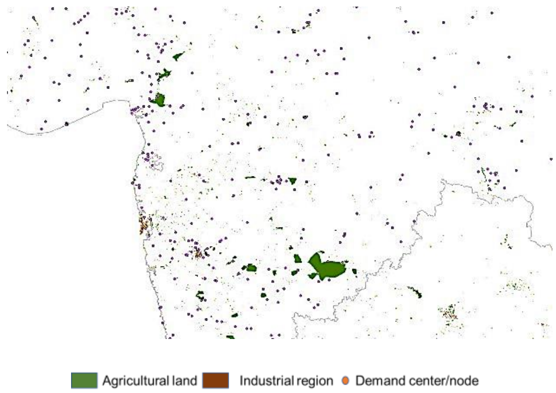


Figure (49) Representation of identification of weightages of demand centers in the WR region

Demand patterns can be immensely complicated, in the case of such a large and complex electricity system like India. These demand patterns can vary with each region, considering the economic growth and population densities in these regions. Additional demand increase due to factors like e-mobility and other unprecedented causes of change in demand should also be considered, as they play a significant role in the development of the demand pattern.

The regional demand is to be distributed at each node, as they form the basis for load flow calculations later during the market simulations. However, the important fact is that the type of demand at each node has to be classified before distributing a certain weightage at the node. As discussed, in a developing country like India, the industrial and domestic residential electrical loads can be expected to form the majority share of the electricity demand. This is a similar case most of the economically developing countries. The Agriculture demand sector plays a unique but vital role in the Indian electrical demand. A Figure (50) shows the classification of the overall demand into demand sectors in India.

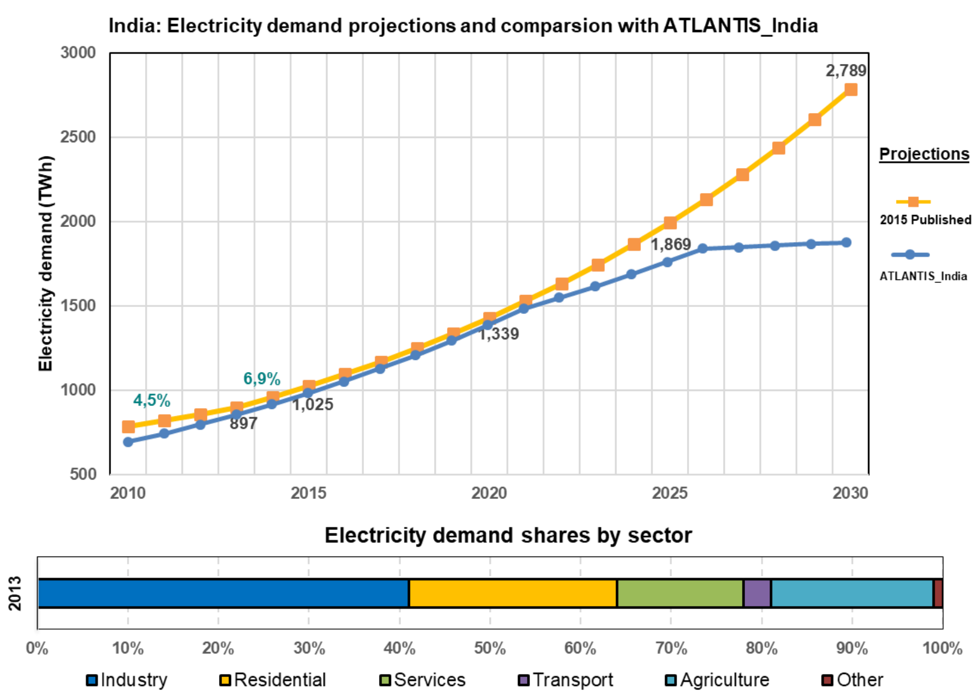


Figure (50) Indian electricity demand projections and demand sectors in the Indian electricity sector, (*Source: CEA, WEO 2015, IEA*)

Therefore, these three demand sectors have to assigned priorities, in the assignment of demand weightages at each node in the model. The demand in the year 2006 is taken as input data for each market region, and is further classified based on the demand development characteristics of each region, based on the major demand sector in each region. For Example, the region NR is hugely populated, hence residential demand profile is more significant, while the West region is an industrially rich region where industrial load profile describes the overall demand characteristics. Similarly, in the case of the SR region, where both industry and residential load profiles are more prominent than the others.

As the country has a large population, the residential demand also has to be considered as priority in the highly populated cities of the all regions. However, agricultural load forms a major part of the intermediate-peak load, as electricity usage in agriculture is mostly during the peak load hours in the day. It is interesting to see the demand behavior for different agricultural practices, and different crop rotation cycles, although the analysis is very much out of the scope of this thesis. Thus, a single agricultural demand profile has been estimated for each region, and has been used in the scope of this doctoral thesis.

The several agricultural, industrial and residential regions in India are identified with the help of GIS maps, and these three maps are overlaid to see the concentration of each region at each geographical node location. These 'region concentrations' are studied further and their influence at the nearby nodes are quantified subsequently, and the weightage at each node for the demand distribution is eventually calculated.

The following summarizes the demand distribution methodology, and gives a clear bird's eye view explanation of the step by step process:

1. Identification of population intensive nodes
2. Classification and identification of SEZs and agricultural lands with GIS maps
3. Identification and study of Industrial and agricultural influence at nodes
4. Check for concentration of minimum demand nodes and quantification
5. Assigning final distribution weightages for demand distribution

3.3.7. Electricity demand evolution

Electrical demand projections in the model are defined based on existing data until the year 2014 and then projected until the year 2050 based on several estimates. The inclusion of energy efficiency directives proposed by the GoI and BEE from 2025 until the year 2030 have been considered [10]. A saturation of demand growth rates from the year 2040 is the final goal, and has been assumed in accordance with the directives. This is an over optimistic approach, but a very important measure as the development of demand growth rates in the sub-continent region is really aggressive, and the directives preventing such a rapid increase in demand have been adamantly supported in this study. A Figure (51) shows the development of electrical demand from the simulation base year until the target year 2050 for each specific model region.

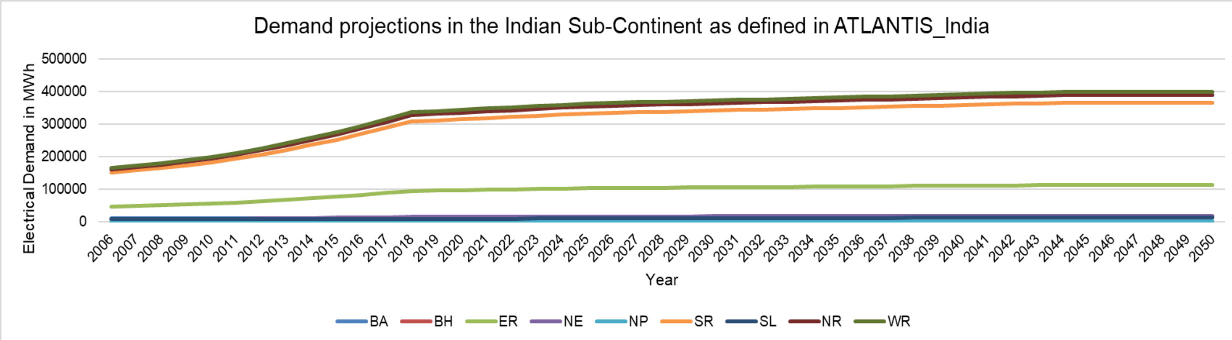


Figure (51) Electrical demand projection in the model regions until the target year 2050

In addition to the linear increase in overall demand per model region, the specific increase of demand at certain nodes have also been implemented. These selected demand centres are chosen in each region, based on the general rate of urbanization and industrialization. The rate of urbanization can be determined by the historical population census data, and demand centres showing a large increase in population have been selected in each region. For example, in the region SR, the cities of Hyderabad, Bangalore, Belgaum, Vishakapatnam and Madhurai showed a large increase in population in the last few years, and thus specific increase in demand has been implemented separately for these demand centres in the simulations. The rate of industrialization is determined by the identification of special economic zones, determined by the GoI. The demand increase at these identified locations within the model region has also been implemented in the course of this thesis.

3.3.8. Other features: Additional Demand

Additional demand resulting from sectors other than domestic, industrial and agricultural sectors can also be implemented in ATLANTIS_India, if and when necessary. The additional load at specific demand centres or nodes can be included with a separate input data file. An analysis for the additional demand due to electro mobility was already conducted during the initial period of this doctoral work, though however, is not included in any scenario defined in the thesis. The input data for the additional demand would be additional weightages at particular nodes, which have to be defined as separate data sets. During the course of the simulation, the additional demand weightage is considered along with the defined nodal demand weightages and then a final weightages of demand distribution are assigned to the particular nodes.

3.3.9. Periodic classification of monthly demand in ATLANTIS_India

The definition data of the physical elements of simulation model form the input database of ATLANTIS_India, and specific scenarios can be defined with this database as foundation. After the specific scenario required for the study has been defined, a timeline for the simulations with a possible target year (based on existing input data) is also set with the help of the user interface (Microsoft access) provided in the scope of the model. With all the input requirements for a simulation met, and the simulation calculations for the timeline defined can now begin.

As discussed in description of the flow of a simulation run, with a consistent scenario definition, a simulation run can be conducted in ATLANTIS_India, only after the check for demand coverage for yearly peak and summer peak defined. If the generation is deemed to be insufficient for peak coverage, additional gas-fired CCGT power plants are added automatically. Once sufficient generation is ensured, ATLANTIS_India then calculates on the basis of monthly demand. The monthly demand in each region is further classified in to 'Peak' and 'Off-peak' periods, based on the regional load duration curve. For the sake of accuracy, these periods are further divided in to sub periods 'a', and 'b', as shown in the figure given below. This definition of sub-period widths is again done as intended by the user.

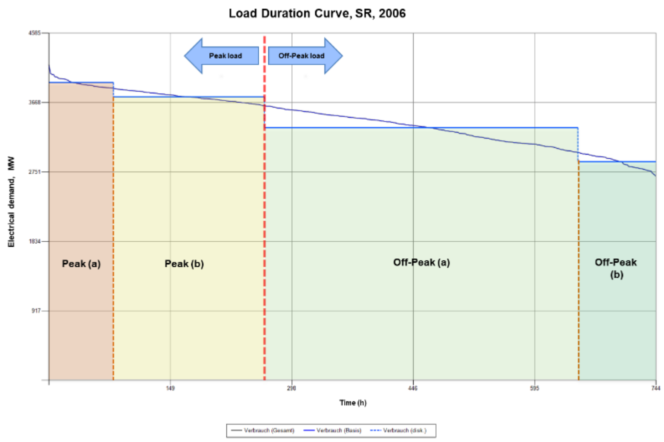


Figure (52) Classification of monthly load duration curves in to peak and off-peak periods, and classification of periods in to 'a' and 'b' subperiods, example, SR region, January 2006.

In the scope of this thesis, all scenarios were simulated with a periodical classification of peak (30/70), off-peak (80/20). This is done to consider the worst-case situations in demand coverage – highest peak and insufficient generation (30 percent of the highest peak loads), and lowest Off-peak and more than enough generation (20 percent of the lowest off-peak loads), particularly in a case of an energy system with high penetration of supply-dependent VRE technologies.

The monthly calculations based on period classification is one of the best ways to ensure simplicity and accuracy in the model, as several stochastic data like generation from VRE capacities like wind and solar PV generally bring in complexities and uncertainties. A simplistic model, with a lower temporal resolution is much better suited to calculate a model with high uncertainties in input data, than a model with high temporal resolution. This reduces the simulation time greatly and provides an optimized accuracy.

Calculations are conducted on a periodic monthly basis in the further course of the simulation run, and load flows resulting from market simulations are then calculated.

3.4. Market pricing in the Indian electricity sector

The Electricity Act of 2003 by the CEA introduced liberalization in the power sector and the market. The Indian energy market is a very complex market, on an overall view. India consists of 29 states, and each state has its own TSO and the authority to make regulations. Furthermore, each state decides on individual energy goals, prices and balance mechanisms for energy generation from RES. However, on a national level, there exists a national balancing organization for the management of secondary and tertiary control. The ancillary services are central, but their prices and rules are decided by the individual states.

Since the year 2003, the Indian energy market has been unbundled. However, the picture concerning regulation looks like a chaotic mixture of centralized and state-run regulations. There is, however, a national agency, the Central Electricity Regulatory Commission (CERC), that drives the development, comparable to the relationship of the European Union and its member states. The Indian energy market is both market-based and state-organized: ancillary services and the power grid are predominantly state-regulated, and the same applies to end-user tariffs.

The market for electricity generation, on the other hand, is open to private companies, and some sub-grids are operated privately. The market is, with further liberalization, on its way to becoming a completely de-regulated market in the future, according to a draft paper published by the CERC [53] in 2018. Through the process, India is looking at Germany and the USA, and their respective energy market designs as references. The India Energy Exchange (IEX) (dd) and the Power Exchange India Limited (PXIL) (ee), are two exchanges created in 2006 after the liberalization of the energy market in 2003, ensure fair competition on single platforms. On both exchanges, there are intra-day and day-Ahead markets. A market for Renewable Energy Certificates (REC) exists on an initial stage, where RECs can be purchased when a generator sells energy to the private sector, instead of the government under a fixed Power Purchase Agreement (PPA).

With the market operations improving considerably with each consecutive year, as well as the synchronization of the transmission grids of all the different power regions as per the One Nation-One Grid initiative, the market is expected to be completely liberalized at the end of this decade. A Figure (53) shows the various bidding zones in India and the day ahead market prices in the IEX.

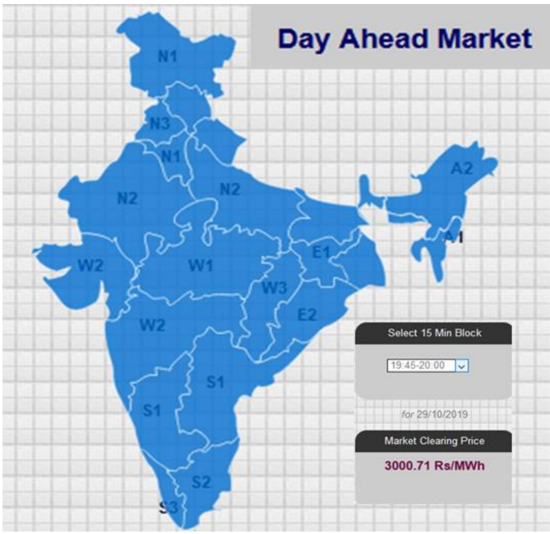


Figure (53) Price zones and Market Clearing Prices in the day ahead market, Indian Energy Exchange Limited [*Source: IEX*]

3.5. Market modelling in ATLANTIS_India

However, in the simulation model ATLANTIS_India, the Indian market is assumed to be completely liberalized (as in the case of the European electricity market), including the markets of BA, BH, NP and SL regions. Having a single market in all the power regions of the Indian subcontinent could be the ultimate solution, to simplify the complex interactions between the power regions, and to progress in to the future with a much more sustainable approach. The market simulations in ATLANTIS_India can be broadly classified in to market models with the inclusion of load flows and physical restrictions, and market model without load flow calculations.

The inclusion of load flow calculations gives us an evaluation of the performance of the transmission grid existing in the model region, with the inclusion of their physical and thermal restrictions to flow of electrical power. The considerations of NTCs as maximum trade limits would improve the economic accuracy in the market simulations, by restricting the maximum possible trade between two model regions. Four interrelated market model types are included in ATLANTIS_India –

1. Energy only Exchange (EoE) market model
2. Overall market model
3. Zonal Pricing market model (ZP)
4. Re-Dispatch Zonal Pricing market model (RDZP)

The following description provides a brief understanding of the pricing mechanism and the interrelation between the several listed market model types.

3.5.1. Energy-only Exchange (EoE) market model (Copper Plate Model)

The Energy-only Exchange (EoE) market model is a calculation mechanism that views the Indian subcontinent as a "copper plate" and determines a market price for a particular period of a given year depending on the supply and demand. The merit order of all power plants of every listed company is determined by ranking the power plants according to the price in ascending order forming the supply curve. The demand in all the regions forms the demand curve. The Market Clearing Price (MCP) can be obtained as an ‘optimal’ resulting price of electricity from the intersection of the two curves.

The supply and demand curves composition are based on the operational level of the companies in the model regions. Thus, each company in the model region is checked to see whether the upcoming (customer) demand can be covered by the available power plant capacity in the model region or not.

The first case (demand that can be met) is shown schematically in Figure (54). The merit order shown here corresponds to the ascending order prices of all power plants belonging to a particular company/model region. The demand (shown in purple) can be covered in this case. Thus, an optimal price P * is formed for a specific power plant KWID *. Those power plants used for demand coverage (all power plants to the left of KWID *) fall into the demand curve shown in Figure (54); those power plants that are not used for supply coverage (all to the right of KWID *) fall into the supply curve shown in Figure (54).

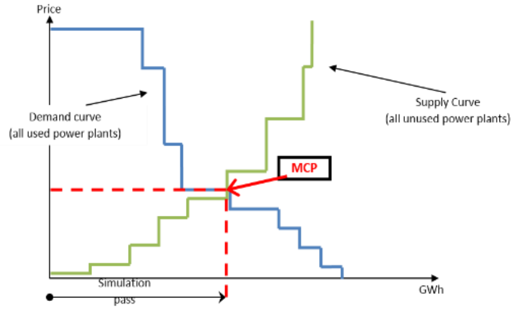


Figure (54) Pricing mechanism based on demand supply curves in the Energy Exchange market model

The second case (when demand cannot be met) is as shown in the right part of Figure (54). The company/ model region creates a shortage of capacity that cannot be covered by its own power plant capacity. The missing capacity as well as the missing capacity price is determined and stored in certain fields, at the end of the supply curve (with a specific power plant ID) of the ‘Tbl_SZ_Decksungsrechnung’.

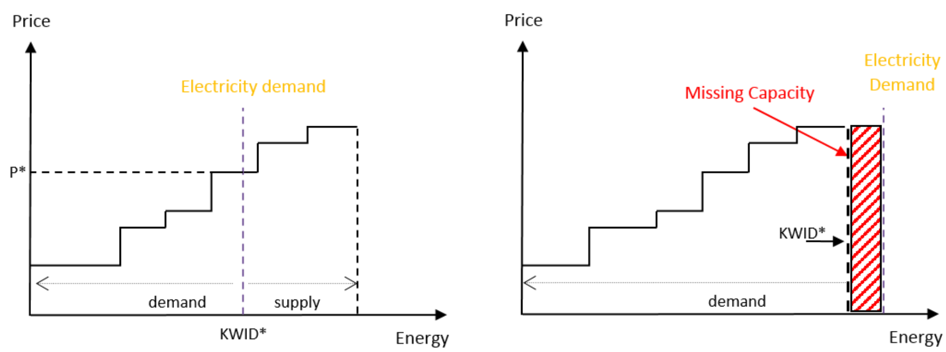


Figure (55) Illustration representing cases in the Energy Exchange market model *when demand coverage is possible (left) and in the case of missing capacity (right)*

The price for the missing capacity is formed by the most expensive power plant of the period including a surcharge. This is necessary to ensure that these calculated prices are the most expensive data points in the demand curve shown in Figure (55) (from left to right).

3.5.2. Overall market model

The Overall market model pursues an economic cost-efficient optimization approach, whereby a cost-optimized use of power plants is determined by excluding any possible market restrictions and considering a levelized production, consumption and transmission structure. Figure (56) provides a schematic representation of the market model approach. Based on given generation (power plants) and consumption structures, a trans-regional cost-optimal deployment of power plants will be determined with the consideration of the given transmission structures (regional and cross-border transmission lines). In the case as shown, the three model regions A, B and C, each with a trans-regional transmission line (in red) are interconnected together. The cost optimization algorithm implemented in this model type ensures that the usage of power plant capacities in all the regions are optimized, considering the physical restrictions offered by the defined trans-regional interconnections for flow of electricity between the model regions.

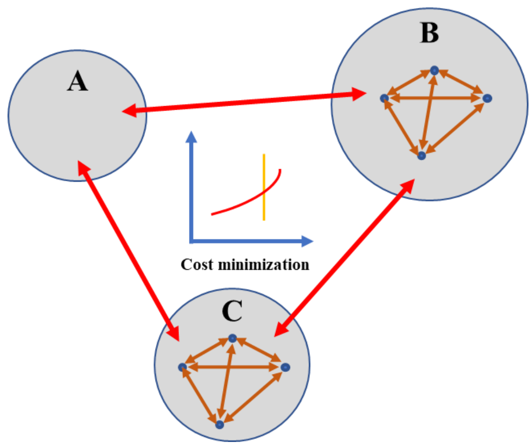


Figure (56) Schematic representation of the Overall market model

3.5.3. Zonal Pricing (ZP) market model

The Zonal Pricing (ZP) market model follows a ‘economic welfare’ optimization approach, which considers the supply and demand curves, as well as physical restrictions on electricity exports and imports for each market (model region) by considering the NTCs defined between the model regions. A market clearing price and the net electricity export quantities are eventually determined after taking into such considerations. The price zones, corresponding to each model region within the simulation model as a copper plates, are defined with a "market" (supply and demand curves), which are then interconnected via NTCs.

On the basis of the given physical restrictions (NTCs), a cost-optimal power plant usage is calculated. This can result in a trade between the different price zones, where the trading always takes place from a "cheaper" price zone to a "more expensive" price zone. Figure (57) provides a schematic representation of such a situation. On the basis of the depicted markets, trade takes place from the cheaper zones (A, B) to the more expensive zones (B, C), if there is sufficient NTCs to support such a trade between the said regions.

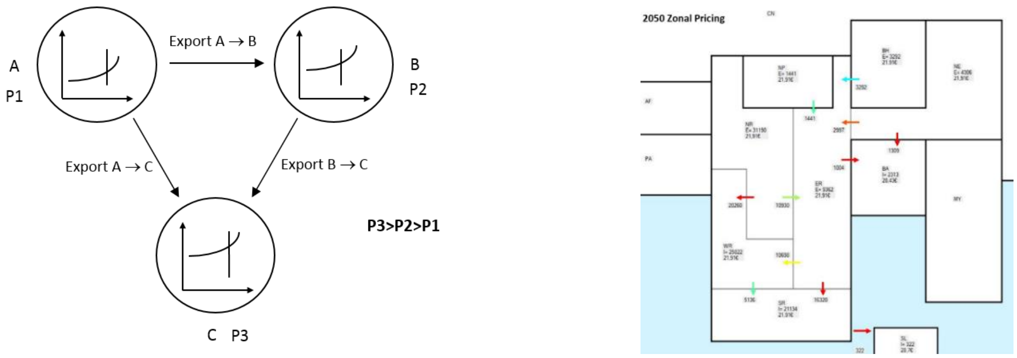


Figure (57) Schematic representation of the Zonal Pricing market model *(left) and an example for visual representation of prices, import/export in the Zonal Pricing market model (right)*

The principle behind the economic welfare optimization algorithm will be discussed eventually at the end of the market model descriptions.

3.5.4. Re-Dispatch Zonal Pricing (RDZP) market model

The Re-Dispatch Zonal Pricing (RDZP) model again follows a cost-optimizing approach that determines the cost-optimal use of power plants, like in the ZP market approach, considering the net electricity export volumes determined in the price zone and the existing production, consumption and transmission structure. In simpler terms, the physical restriction of the transmission lines within and between each region in the model is taken into consideration. This model is therefore an extension of both the overall market model and the ZP market model.

Since physical restrictions within and between model regions are considered, the model brings in a factor called ‘redispatch’. If there is insufficient transmission capacity for power flow between a generation capacity and the demand center, the redispatch ensures demand coverage at the demand center by ensuring enhanced deployment of power plants in areas with enough transmission capacities. Within the simulation model, a distinction is also made between regional and interregional redispatch. Figure (6) provides a simplified illustration of this.

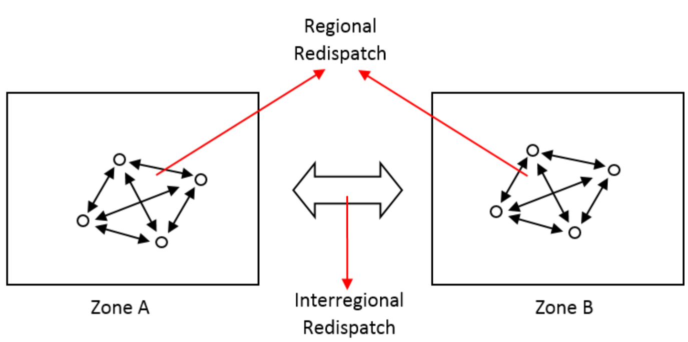


Figure (58) Schematic representation of Regional and Interregional Redispatch, *in the Re-Dispatch Zonal Pricing market model*

A regional redispatch always takes place in ATLANTIS_India within a specific region. The interregional redispatch is similarly conducted between two regions. The limits of interregional trade, the net exports per region, are hereby then calculated by the zone price model considering the NTCs. These net export limits are included as new limiting conditions in the RDZP market model. Furthermore, tolerance limits for each region can be specified with regards to the interregional redispatch. The RDZP market model combines the trading restrictions offered in the ZP market model and the physical restrictions to power flow offered by the transmission grid within and in between the regions, emulating the reality of electricity market in the sub-continent with as much accuracy as possible.

3.6. Market simulation mechanism in ATLANTIS_India

In the scope of this thesis, the RDZP market model type, with considerations to both the NTC trading limits and physical restrictions of available transmission infrastructure, is used to simulate as-close-to-reality-as-possible scenarios for the electricity system in the Indian subcontinent region until the target year 2050. The simulation flow is also explained as shown in the figure (58). The RDZP market model approach takes the results for zonal market pricing from the ZP market model and the DC-OPF load flow calculations from the Overall market model and calculates a cost minimum unit dispatch for each power plant within the NTC-coupled price zone.

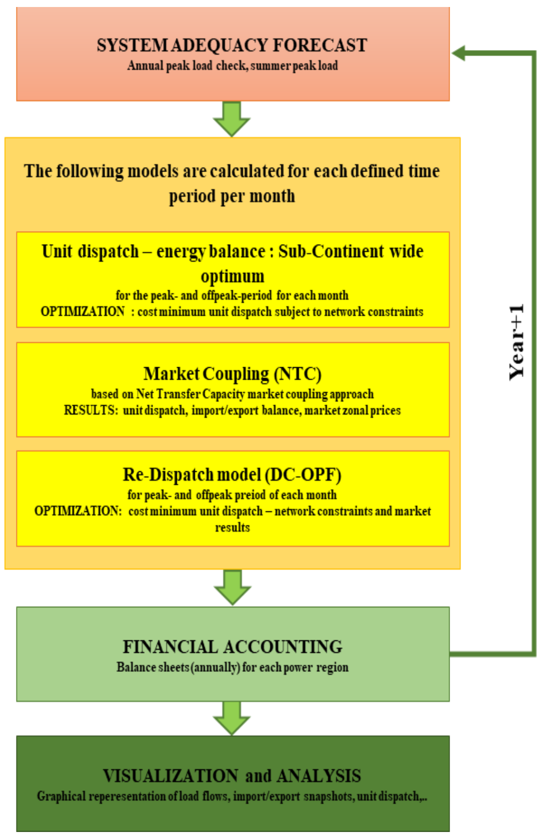


Figure (59) Representation of simulation flow in ATLANTIS_India with the RDZP market model approach

The RDZP market model follows a cost-based optimization procedure [8]. Along with the NTC based market coupling algorithm (cross border constraints), the objective function is defined as the maximization function for the economic welfare by minimization of overall generation costs, from an electricity economics perspective. The economic welfare-maximization function is described as follows.

$$Max \qquad \left\{\sum_i \left[\sum_n \left(qD_{n,i} \cdot pD_{n,i}\right) - \sum_a \left(qS_{a,i} \cdot c_{var}S_{a,i}\right)\right]\right\} \tag{E2}$$

$s.t.$

$$qS_{a,i} \leq qS_{max_{a,i}} \tag{E3}$$

$$qD_{n,i} \leq qD_{max_{n,i}} \tag{E4}$$

$$export_{i\to j} - import_{i\to j} \leq NTC_{i\to j} \qquad \forall(i,j|i \neq j) \tag{E5}$$

$$\sum_k export_{k\to j} - \sum_k import_{k\to j} \leq TP_{k\to j} \qquad (k \subset i \land j \notin k) \tag{E6}$$

$$\sum_a qS_{a,i} - \sum_n qD_{n,i} + \sum_{j\neq i} import_{i\to j} - \sum_{j\neq i} export_{i\to j} = 0 \qquad \forall i \tag{E7}$$

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

From the welfare-maximization function defined, it can be seen that the economic welfare in a specific region depends highly on the possible amount of exports/imports resulting due to generation in the region, limited by NTC values defined between the import/export regions. The cost-optimization based on marginal pricing in the two regions undergoing import/export, makes sure that the overall price in the importing region decreases as a result of importing from a region with cheaper electricity price. Similarly, the exporting region observes an increase in prices, as a result of the social welfare optimization process carried out. The NTC values set a limit to the maximum possible import/export, there by restricting the overall possible welfare due to import/ export.

The load flow calculations in the simulation model, follow a DC-OPF [55] based on linear DC load flows. The calculated DC load flow considers only the active power flow in a linearized form, while ensuring an extended economic dispatch with a cost minimization approach. The following equations (E8) (E9) provide a brief explanation for the AC load flows and the assumptions considered resulting in the DC-OPF approach followed in ATLANTIS_India.

$$P_k = \frac{U_k^2}{Z_{kk}} \cos(\psi_{kk}) - \frac{U_k U_m}{Z_{km}} \cos(\Theta_k - \Theta_m + \psi_{km}) \qquad \text{(E8)}$$

$$Q_k = \frac{U_k^2}{Z_{kk}} \sin(\psi_{kk}) - \frac{U_k U_m}{Z_{km}} \sin(\Theta_k - \Theta_m + \psi_{km}) \qquad \text{(E9)}$$

$$\frac{1}{Z_{kk}} = \left| \frac{1}{R_{km} + jX_{km}} + G_k + jB_k \right| \qquad \psi_{kk} = \arg(Z_{kk}) \qquad \text{(E10)}$$

$$\frac{1}{Z_{km}} = \left| \frac{1}{R_{km} + jX_{km}} \right| \qquad \psi_{km} = \arg(Z_{km}) \qquad \text{(E11)}$$

k,m .... nodes
P_k..................... active power flow from k to m, at node k [p.u.]
Q_k .... reactive power flow from k to m, at node k [p.u.]
Θ_k .... voltage angle at node k [rad]
R_{km} .... real part of the series impedance (resistance) between k and m [p.u.]s
X_{km} .... imaginary part of the series impedance (reactance) between k and m [p.u.]
Ψ_{km} .... angle of the series impedance Z km between k and m
G_k .... real part of the shunt admittance (conductance) at node k [p.u.]
B_k .... imaginary part of the shunt admittance (susceptance) at node k [p.u.]
Ψ_k .... angle of the Zk at node k

The power flows within the transmission lines are defined with a maximum limit for power flow in the particular line, while assuming only active power is transmitted in the grid. In order to reduce the complexity and the computational calculation time, the AC load flow equations in the power system can be defined and simplified by using several validated assumptions [55] [56].

- The active power losses in equations (E8) and (E9) are neglected, (R_{km}=0, $\Psi_{km}=\pi/2$)
- Shunt elements are neglected (G_k=B_k=0)
- Small voltage angles differences are assumed, and this leads to the approximation of $\sin(\Theta_k - \Theta_m) \approx \Theta_k - \Theta_m$ and $\cos(\Theta_k - \Theta_m) \approx 1$
- Assumption of a flat voltage profile at all nodes in the network (U_k=U_m=1 p.u.)

The result of the usage of such assumptions is the linear DC flow in equation (E12), which focuses only on the active power flows in the transmission network.

$$P_k = Y_{km} \cdot (\Theta_k - \Theta_m) = \frac{\Theta_k - \Theta_m}{X_{km}} \qquad \text{(E12)}$$

Based on several studies [52][56][57][58], the usefulness of DC load flows for power flow analysis in larger interconnected networks with high transmission voltage levels have been confirmed. Thus, it can be concluded that DC load flows can provide a great approximation of power flows in networks where the ratio between the series reactance (X) and resistance (R) is not less than the factor 4 (by definition of transmission line parameters). The Equation (E12) forms the basis of the DC-OPF approach, where the objective function of the common DC-OPF algorithm minimizes generation costs subject to transmission constraints, based on the DC load flow equation and energy balances at the nodes.

3.7. Business models in ATLANTIS_India

A techno economic model providing the business model integrated in to a strategy is a valuable asset, since several inferences for investment related decisions can be taken by the investing companies in a liberalized market. ATLANTIS_India provides such a dimension, and could be used to evaluate the business models of all the investing companies defined in the input data. The model gives a detailed Profit and Loss statement, Balance statements and the capital stock of each model region or company based on their respective capacities installed. 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. This section provides a brief overview on the possible economic results from a simulation in ATLANTIS_India.

3.7.1. Company portfolios

The data on investing companies is associated and defined along with the input data. The companies are also linked with their invested power plant capacity in the power plant input data in ATLANTIS_India. The model includes the investment data of over 200 investing companies, defined with respect to each model region. Several centrally owned companies are defined as separate companies associated with investments in each specific model regions. State owned and private companies with investments in other power regions are also differentiated based on the region in which the invested capacity falls. A Table (15) gives a representation of the companies defined in the model ATLANTIS_India. The investment portfolios of each company can be visualized separately, and the income generated through their specific investments can also be analysed.

Model Region	**Companies**	**Major investor companies**
BA	11	Bangladesh Power Development Board (BPDB)
BH	6	Bhutanese Royal Government (BRG)
ER	18	National Thermal Power Corporation Limited (NTPC)
NE	17	NEEPCO, NTPC
NP	7	Nepal Electricity Authority (NEA)
NR	36	National Hydro Power Corporation Limited (NHPCL), NTPC
SL	18	Ceylon Electricity Board (CEB)
SR	56	National Atomic Power Corporation of India (NAPC), NTPC, NHPCL
WR	35	NAPC, NHPCL, NTPC
Total	204	NTPC, NHPCL (investment across regional borders)

Table (17) Power plant companies defined in ATLANTIS_India

3.7.2. Financial balance sheets

ATLANTIS_India also provides an opportunity to generate balance sheet for the power plant fleet of each model region defined in the input data, and this statement can be used to economically evaluate overall wealth (capital asset of the fleet) in the particular model region. Furthermore, the capital assets resulting from specific technology types can also be visualized for each region, thereby providing a possibility to evaluate specific power plant technology types in each specific region. Having access to calculated balance sheets in a specific format simplifies the analysis and saves a major amount of time in evaluating the economic performance of the model region. The Figure (60) visualizes the scheme of balance of statements for a particular company defined in ATLANTIS_India.

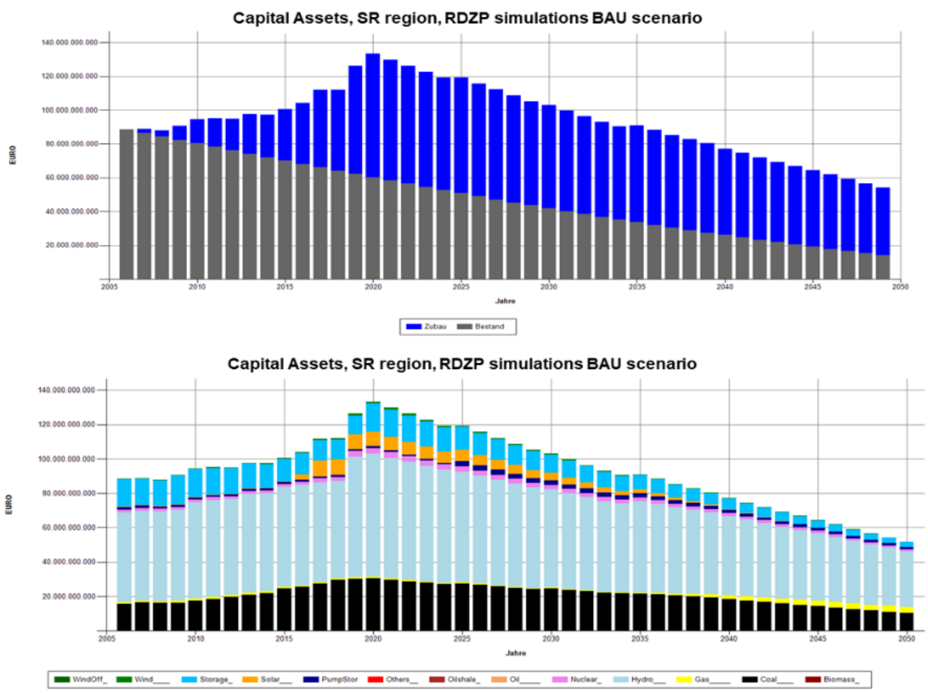


Figure (60) Example for the visualization of the balance sheets generated in ATLANTIS_India

3.7.3. Profit and loss statements

ATLANTS_India includes the profit and loss calculations for the power plant fleet of each specific model region defined, based on the specific investments in power plant capacity, the income and the expenditures involving in operation of such a power plant fleet. Depreciation values of company specific investments can also be calculated and displayed, giving a rough economic evaluation of the power plant fleets. Based on the evaluation, several inferences can be made, and specific investment related suggestions can be offered to the concerned power plant company. The Figure (61) represents the scheme of profit and loss statements for a region defined in ATLANTIS_India with expenditures (Aufwand) and earnings (Ertrag)

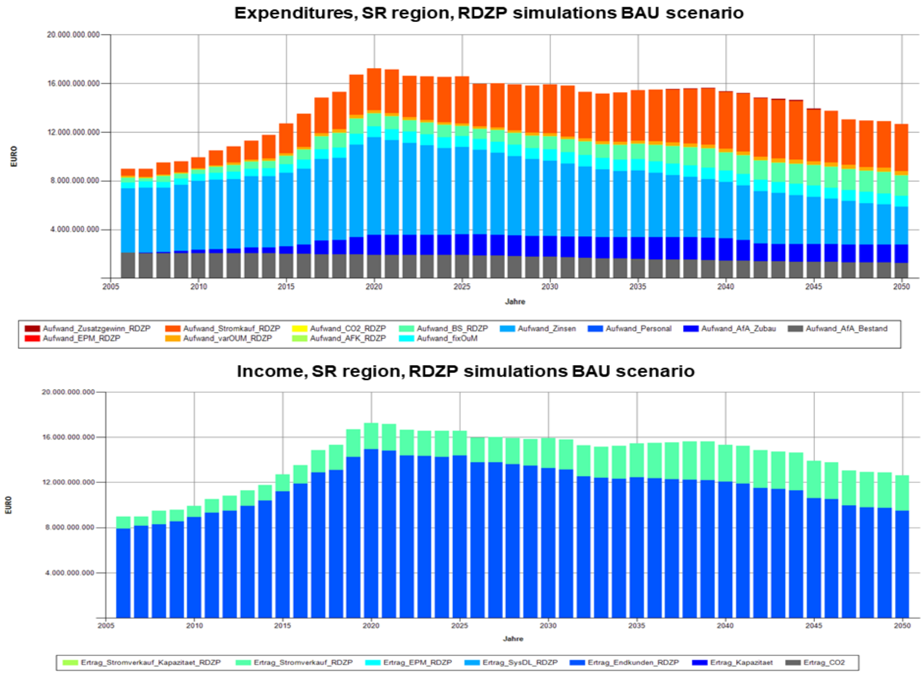


Figure (61) Example for the visualization of the profit and loss calculations – (top) Expenditures and (bottom) Income- generated in ATLANTIS_India for the SR region, Re-Dispatch Zonal Pricing (RDZP) market simulations for BAU scenario

3.7.4. Capital stock calculations

Capital stock can be economically termed as the long-term wealth or fortune of a company. The capital stock basically represents the total amount of capital invested by a company on assets. The capital stock concept for evaluation of assets highlights the preservation of long-lasting assets over their nominal capital. In the case of an electricity system, assets are power plants, transmission lines, and transformers stations. All such assets are invested with long term usage in mind. Each of the power plant types have specific investment costs, fixed variable costs and other economic parameters. Most of the power plants technologies have high capital intensities, so a capital stock intensive plan to optimize the technology specific investments and the evaluation of the usefulness of installed power plant types is really important.

The accounting of such assets in the books of an energy company is usually done using the historical acquisition values [59], which tend to under evaluate such assets, as they do not consider the real replacement values. In the case of evaluation of assets which are invested upon with long term usage in mind, this under-evaluation could lead to serious complications in the futuristic planning of the energy sector. This would mean that a power plant installed in the 1980s would cost almost the same as a power plant installed in the year 2020.

However, capital stock calculations involve the use of replacement values over the lifetime of the asset, which is a better measure of the asset value than historical acquisition values. This measure of capital stock is called the Gross Capital stock (GCS), which does not take the depreciation values into consideration. The GCS values form the basis for the Net capital stock calculations (NCS), which is a much fairer measure of the asset value- as it considers the concept of depreciation. Depreciation considers the decrease of the value of assets over the usage and lifetime, year by year, until the end of its technical useful life.

3.7.4.1. Capital Stock evaluation of power plant assets

Normally, power plant types have specific investment costs, based on the generation technology, the involved fixed assets, availability of fuel and their geographical location. However, in the scope of this thesis, the investment costs are only specified per MW of generating capacity by power plant type. The NCS calculations can also differ based on the technical and economic useful life times of the defined power plant assets. Considering the technical useful lifetimes would be a fair assumption as the power plant operates throughout the technical useful life than the economic lifetimes, which is generally mentioned in the accounting books of the investing company. The technical and the economic useful life times of various generation technology types are defined in the simulation model ATLANTIS_India, as mentioned in the Table (16) below.

Power Plant Type	Economic Lifetime (years)	Technical Lifetime (years)
Biomass	20	25
Lignite coal	25	35
Gas Turbine	40	45
Gas CCGT	35	45
Bituminous coal	45	50
Nuclear BWR	55	80
Nuclear CANDU		
Nuclear PWR		
Nuclear Th_FBR	60	100
Oil fired	40	45
Solar PV	25	30
Pumped Hydro	60	100
Dam Hydro	60	100
Run of River Hydro	75	120
Wind onshore	25	30
Wind offshore	20	30

Table (18) Economic and Technical Useful times of power plant assets by technology type defined in ATLANTIS_India

The depreciation values of the installed power plants in each region are also taken from the simulation results of the economic model, from the base simulation year till the target year. The capital investment, interest rates, fuel costs, personnel costs and other costs are all used to calculate the GCS values. Subsequently, the NCS values are also calculated. The investment values, when not available are scaled down from the EU values, using PPP comparisons, as discussed already

The need for calculation of capital stock of the power plant fleet is to avoid many of the conventional assets being stranded. An abrupt transition from conventional power to RE power could create implications for the financial sector of the Indian energy sector. This is because of the relatively younger age of most of the installed capacity of the power plant fleet. The Figure (62) shows an example for the power plant ages in the region SR by year 2030, showing a relatively large share of the capacity being under 20 years of age. In this thesis, as mentioned before, the economic lifetimes of all conventional power generation technologies have been assumed to be around the range of 25 - 40 years, and the technical life time to be at least more by 10 years, depending on the capacity size and the type of generating technology used. An abrupt transition would mean that the conventional power plants have to be shut down at least five years before the actual end of their technical lifetimes.

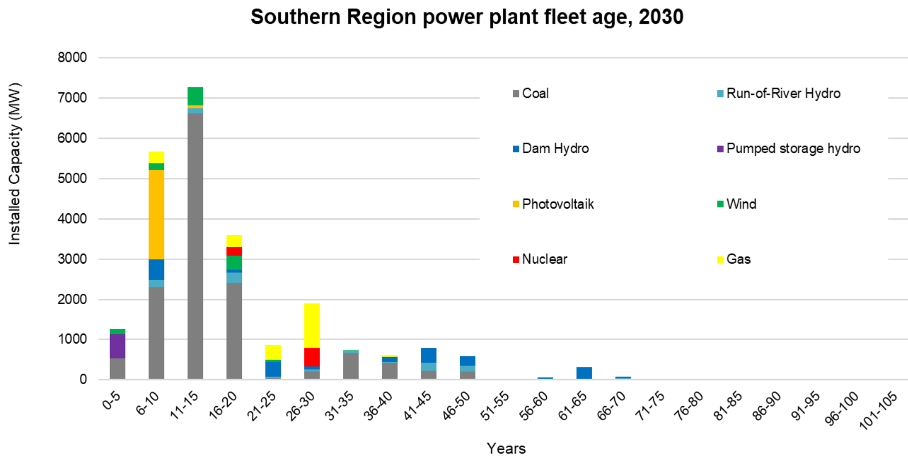


Figure (62) Age structure of the power plant fleet in the region SR, 2030

Furthermore, most of the relatively younger power plants are invested by the Indian private sector with respect to the increasing share of liberalization in the market since its inception in 2006. Stranding of such assets would mean heavy financial losses to the private sector, and that would push the private sector towards bankruptcy, in turn resulting in a decrease of interest for further investments in the power system.

By completely disregarding the stranded assets, with enough support and financial aid from the government, if further private investments in RE power are to be continued, it makes logical sense to invest in power plants with longer technical life times. Therefore, it becomes significant for the policy makers, to invest heavily on capital intensive power plant technology types, especially with a longer lifetime. The capital stock calculations give valuable insights to the worth of each power plant technology types in their respective regional capacity mix, within the complete timeline until the simulations.

3.8. Automated Gas fired capacity addition

ATLANTIS_India also includes the possibility of adding a pre-defined capacity of gas-fired CCGT power plants, in case of missing capacity. As explained in the market model descriptions, the automatically added power plants are designed to be the most expensive power plants in the model region, and are only added in case of missing capacity during the demand coverage check. The automatic CCGT additions are said to be carried out by a ‘Intelligent Investor’, adding capacities at specific nodes where demand coverage is not possible due to the missing capacity. This addition by the ‘Intelligent Investor’ is done at the specific node after ascertaining the transmission capacities available around the given node, and after checking if other power plants in the model region or other interconnected regions would be able to satisfy the demand at the given demand centre or not.

The gap between demand and supply in the sub-continent region has already been compensated in the model ATLANTIS_India by adding extra CCGT capacities in the input data, so that the automatic gas additions can kick in only at the latter half of the simulation period, when and if necessary.

3.9. Automated refurbishment of renewable energy capacity

As renewable energy technologies like Solar PV and Wind power are characterized by smaller technical lifetimes than other thermal and hydro power plant types, an additional option for the inclusion of automatic refurbishment of renewable power capacities has also been implemented in the simulation model. At the end of their technical lifetimes, the solar PV, wind -on and offshore, and hydro power plants are automatically re-installed with the similar investment costs and other variable costs (if any). The option whether to include refurbishment or not during the scenario development in the simulation model provides an opportunity to test possibilities where motivation for renewable energy expansion becomes more and more bleak in the later stages of the timeline until 2050. In the scope of this thesis, all the scenarios implementing an increased share of renewable shares of Solar PV, Wind On- and Offshore or Hydro power plants have been defined with an automatic refurbishment of the capacities during their respective simulation timelines.

3.10. Visualization tool 'ATLANTIS VISU 2.0'

As discussed, ATLANTIS_India provides a large spectrum of simulated results, ranging from electricity prices in model regions (economic), to the load flows in the transmission network (technical). Results based on prices are relatively easier to analyse, but when it comes to load flows and the 'loading' in the transmission lines, evaluation based on values become increasingly complex and difficult. For the said purpose, a visualization module called 'ATLANTIS VISU 2.0' was also developed along with the model ATLANTIS at the IEE, for easier and more effective evaluation of results.

The VISU 2.0 is a very effective add-on tool which imports simulated scenario data from the simulation model and visualizes the actual load flows and the loading of transmission lines in the network, thereby providing a clear understanding of the simulated load flows. The VISU 2.0 also gives an option to visualize several other results like zonal pricing, import/export, power plant fleet age structure, generation mix and carbon dioxide emissions for each model regions in the simulated scenario.

ATLANTIS_India exports the necessary result data in the form of .csv and .gms files, which are created during the simulation process. The VISU 2.0 reads these exported data files to graphically display the data in two different possible ways. One way is to use the data exported by ATLANTIS_India and display them using SharpMaps, the other way would be to export the resulting data in .kml format and display them using google earth. In the scope of this thesis, SharpMaps are used to visualize the results, for the sake of clarity and simplicity. The visualization module has been used in this thesis to visualize load flows and loading of the transmission network, in each specific scenario.

CHAPTER 3

Scenario development for the Indian Sub-Continent

4. Energy planning and strategies in India

As discussed, the energy planning and regulation is done by a set of regional regulatory bodies governed by a central regulatory body of the MoP, GoI. Each regional regulator initially conducts a large-scale analysis in their respective fields of interest, and then a combined approach is suggested by the MoP after careful evaluation of the proposed strategies. The MoP however, initially sets the deadlines and the overall theme in the planning process. The long-term energy plans in India are proposed on a five-yearly basis, along with the five-year plans proposed by the planning commission of India. Furthermore, several short-term plans are also individually proposed by the MoP, with regards to the situation at hand. This section summarizes the several strategies proposed by the MoP, GoI for aiding the energy transition process in the country.

4.1. Utility-scale renewable strategy (centralized)

A centralized generation strategy involves installations of large capacities of renewable energy in regions of higher potential availability and fed in to the overall grid for usage throughout the country. The government of India proposed such a strategy involving solar PV, solar Thermal CSP, onshore wind, and off shore wind power installations. The Figure (65) illustrates such a strategy outlined by the MoP, GoI. The strategy involves installations of more than a 100 GW of solar PV in the north-western wastelands in the NR and WR regions, and in the SR region, along with minor PV installations in the mega-watt range in the ER and NE regions. To also include solar thermal potential, CSP installations are also planned on a long-term basis, in the Thar Desert region in the north western part of the country. Onshore-wind installations of more than 75 GW have been planned in the hilly regions in the SR and WR regions. wind offshore development regions are also being proposed in the western and southern coasts of the country, along with a few zones in the south eastern coast. This strategy, would easily achieve the India's renewable targets, almost within the given time frame. However, the investment required for such a strategy would really pose a considerable challenge to the Indian power sector. So, a considerable amount of investments is expected to come from international funding

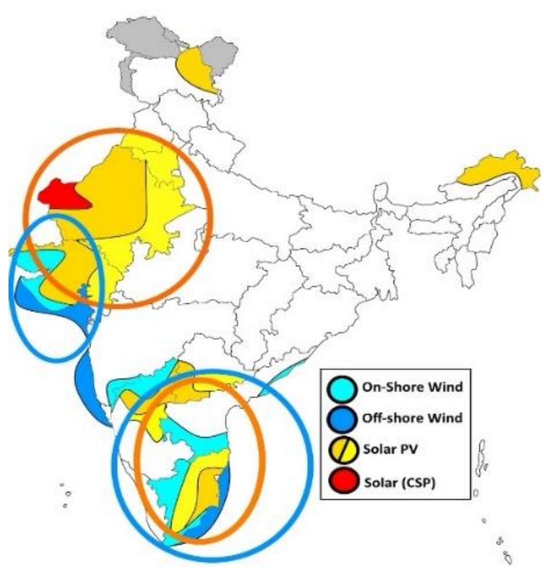


Figure (65) Centralized strategy for Renewable Energy addition in India

4.2. Distributed renewable strategy (decentralized)

A decentralized generation strategy revolves around the concept of improving the number of off-grid small scale solar PV and wind installations throughout the country. The feed-in to the grid happens only during excess electricity generation. This strategy provides a range of benefits, along with a premium feed in tariff, investment support, and loans at smaller interest rates, encouraging the concept of 'Prosumers'. Implementation of several small-scale installations of different technology types in regions also improves the technological diversification of the power sector. The different RE technologies planned in relation to the climatic conditions in the five different power regions in India are as shown in Figure (66).

Along with the NISE, the MoP has calculated a potential of 40 GW (just with solar PV rooftop generation) via this strategy [23][54]. This strategy was initially planned to be proposed to rural areas with limited transmission connectivity, for a pre-determined (fixed) load period. With limited access to electricity, most of the rural households are now equipped with cheap battery storage systems - Uninterrupted Power Supply (UPS) units. With the implementation of small scale RE generation capacity in these households, electricity can be stored during excess generation during the day (small peak), and eventually used for the partial coverage of the evening peak (large peak). However, the importance of such a strategy is that the responsibility of investments is shared with the private consumer. The draw backs of such a scenario would be fulfilment of the regional capacity obligations/ targets within the specified time duration. This would also bring in the possibility of improved chance of electricity system performance, with the V2G and G2V strategy for storage as proposed in the e-mobility strategy (NEMMP), as such a strategy would only be feasible with energy systems with a small size.

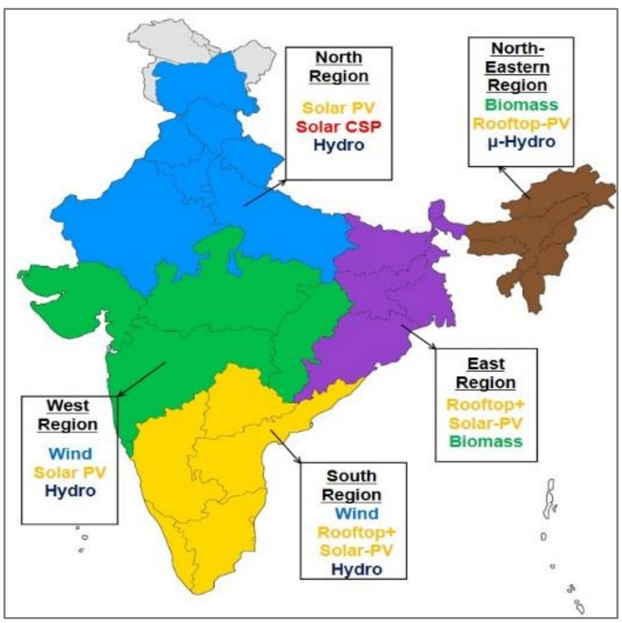


Figure (66): Different power regions and a De-Centralized generation strategy

4.3. Large hydro power installations in Nepal and Bhutan

With several challenges to large hydro power expansion in India, the GoI has explored the possibility of mutual cooperation and investments in large hydro and pumped hydro power plants in the Himalayan regions of Nepal and Bhutan. Both the countries have long standing friendly diplomatic relationships with India, and several of the existing hydro power plants in the two countries are constructed by Indian companies. Thus, a possibility for an accelerated expansion of large hydro capacities in Nepal and Bhutan could be a real-time solution to India's future challenges due to high penetration of VRE sources. This strategy has been explored in great detail by defining a scenario in the course of this study, and the results are analysed.

4.4. Other strategies

The Indian electricity sector has been riddled with challenges mostly due to the sudden growth in the manufacturing sector and the industrialization of the country. The country has always favoured nuclear energy usage for peaceful purposes, and have always had great ambitions in the expansion of its nuclear capacities, as it can be one of the simplest ways to provide a solution to two of India's major challenges: energy access and energy related emissions. As such, several strategies, including short- and long-term strategies were developed around nuclear energy.

4.4.1. 'Thorium' HT-FBR capacity expansions

Research on Thorium based high temperature fast breeder reactor technology (HT- FBR) in India is growing at a large pace, with one reactor unit already under testing period since the year 2017. India's plans of doubling its nuclear based capacity in the near future can explain the amount of effort seen in research of this specific technology. This technology is proven to be much safer than PWR technology and is capable of generating a significantly smaller amount nuclear waste after each cycle. The amount of Thorium deposits in India is one of the largest in the world, and can easily help the nuclear-trade restricted country improve its nuclear based capacities. The promotion of the use of nuclear energy technology is really risky, as it leads to the possibility of manufacturing mass destruction nuclear weapons.

A single HT-FBR reactor is now operational (under testing till the year 2025) in the country, and another unit is expected to be operational in the end of the year 2019. In the scope of this thesis, though the use of nuclear based technologies is seriously discouraged, for the sake of curiosity, a scenario with aggressive nuclear capacity expansion has been simulated and the results analysed. In this scenario all the newly added capacities in India after the year 2025 are based on HT-FBR technology.

4.4.2. Nuclear capacities in BA and SL

Based on several signed treaties, India and Russia plans to build nuclear power plants in Bangladesh and Sri Lanka. Russia has been commissioned to build a BWR power plant of 1000 MW capacity in Bangladesh, while India has been contracted with the task of building a BWR plant in Sri Lanka by the year 2025. These nuclear power plants are expected to improve the energy situation in both countries, as Bangladesh heavily relies on coal and natural gas for power, whereas the use of oil for a large share of the electricity generation in Sri Lanka has been facing challenges with the volatile nature of oil prices (58). The nuclear power plants are also expected to cement the friendly ties of India with both the countries. Several cross-border lines between India and the two countries have been planned, to improve the quality of the electricity supply in the whole sub-continental region.

5. Scenario development in ATLANTIS_India

Based on the discussed strategies for Energy planning in the Indian subcontinent, four specific possible scenarios are defined in the course of this thesis. Each of the scenario takes in to account major pointers from the above discussed strategies, and evaluation of the simulated results of such realistic scenarios gives a complete and a useful understanding of the energy future in the Indian Sub-Continent region. Several factors were taken in to consideration, to implement most of the over ambitious energy targets in the Sub-Continent region, and scenarios were defined to be as realistic as possible.

5.1. Methodologies of scenario definition in ATLANTIS_India

The scenario definition in the simulation model ATLANTIS_India can be done through varying several different input data, depending on the type of analysis to be conducted. Different scenarios can be defined by including different power plant capacity addition strategies, by reinforcement or decreasing the transmission capacities, by varying several economic parameters like inflation rates, interest rates, depreciation rates, etc., by implementing different fuel price evolutions, or by introducing different demand projections and/or including additional demand data.

5.1.1. Power plant capacities

Specific scenarios can be defined by increasing, decreasing or introducing new shares of specific power plant technologies within a model region. Such a scenario brings in the possibility of evaluation of the impacts of specific technology types for each of the model regions. For example, a scenario for the diversification of power plant portfolio in the Indian region could be defined in a simple way by increasing the share of RE and other non-conventional technologies and limiting the expansion of coal- and gas-fired capacities. The simulations of such a scenario would not only evaluate the effect of diversification of power plant portfolio, but also highlight positive or negative impacts of certain power plant technology types. In this thesis, all the scenarios discussed have been defined by varying the input data of specific technology types.

5.1.2. Fuel prices

Different evolution of fuel prices can provide a wide spectrum of possible scenarios, especially for the Indian sub-continent as a large share of electricity in the region is generated by conventional technologies burning fossil fuels. With both domestic and imported coal and natural gas being relatively less expensive in the region, variations in fuel price evolutions in the region can be implemented as a part of the scenarios defined. In this thesis, a single common evolution of fuel prices has been assumed, with the prices of coal, natural gas and oil largely increasing after the year 2020. This makes the analysis of the scenarios easy and simple, as the thesis is largely oriented towards transition from these conventional fuel to RE power.

5.1.3. Transmission capacity restrictions

The changes in transmission line infrastructures in the overall network bring in restrictions for power flow within the model region, and between model regions. The definition of NTC restrictions also can play a major part deciding exchange of power between model regions, and limiting the regional and the interregional redispatch possible. Also, the effectiveness of power plant capacities in regions outside India can also be analysed by restricting/ increasing the interregional transmission capacities. In this thesis, transmission infrastructure is assumed to be similar in each scenario, for the sake of simplicity. This also brings in the possibility to evaluate the transmission infrastructure planned by the several TSOs in the model regions, with the change in power plant mix in the case of each scenario defined.

5.1.4. Evolution of electrical demand

Different evolution timelines can be defined by varying the demand growth rates for each model region in the input data for ATLANTIS_India. The hourly demand in the simulation base year 2006 is taken as input data. A linear increase of demand at all nodes within a model region can be carried out by defining a ‘growth rate’ timeline in the parameter definition input tables. In the case of this thesis, the improvement of energy efficiency is largely encouraged, and a smaller rate of annual growth rate has been assumed after the year 2030. Region specific scenarios can also be defined by changing the demand weightages of specific nodes in each year, in conjunction with the linear growth rates for regional demand.

5.1.5. National economic parameters

Changing national economic parameters like inflation rates, interest rates, depreciation rates, economic development factors and many others actually bring in a macroeconomic perspective to the definition of a scenario in ATLANTIS_India. The input data for the national economic parameters is defined as a timeline of such parameters for each model region, thus giving a large overview on the macroeconomic situation in the Indian sub-continent. Extreme-case scenarios can be implemented by varying the evolution of such economic parameters, by limiting the economic situation in concerned model regions. A single common evolution of economic parameters for each model region has been assumed in the definition of scenarios in the scope of this thesis. The evolution of economic parameters in each scenario assumes the mutual economic development in the model regions of the Indian sub-continent, with decreasing interest and inflation rates, and an increase in the growth of economic development.

5.2. Study scenarios and visualization

For the sake of validation of input data and initial simulated results, a base scenario (2006 – 2020) for the Indian sub-continent was defined. The data required for the definition of such a scenario was derived from the Current Policy Scenario (CPS), India Energy Outlook, WEO 2015 [31], published by the IEA. Scenario definition in ATLANTIS includes defining the overall increase in electricity consumption, change in fuel prices, projecting additional installations of a specific power plant type, defining the economic parameters like depreciation rates, interest rates, inflation rates and many more specific data inputs in the model. All the required information for defining and validating the base scenario was taken from the IEO, and is as shown in the table below.

In the current policies scenario mentioned in the IEO, all new coal fired power plants built after 2035 are ‘clean’ coal technology, and the existing coal fired power plants are assumed to operate until the end of their lifetimes. These power plants are to be replaced with a more efficient and much cleaner smaller CCGT capacities However, the base scenario defined was only simulated until the year 2020, as it is only considered for validation of simulated data. Several other scenario specific assumptions are considered later on (after 2020 in the case of scenarios defined in this thesis).

Power plant type in the CPS	**Installed Capacity 2013 (GW)**	**Installed Capacity 2020 (GW)**
Coal	154	238
Oil	7	9
Gas	22	43
Nuclear	6	10
Hydro power	43	58
Biomass	7	10
Wind	21	44
Solar PV	3	15
Solar Thermal	0	1
Wind offshore	0	0

Table (19) Base- power plant scenario definition for India Source: IEO, IEA, Current Policies Scenario

With the energy transition goals, sustainability and long-term economic goals in mind, four different scenarios were designed for the scope of this study. These scenarios were designed based on the extent of liberalization of the power sector, and the extent of renewable transition in mind. The input data was initially validated with available database until the year 2017, and subsequently validated for using the above-mentioned base scenario until the year 2020. The four scenarios discussed and studied in this thesis are as follows.

1. Business As Usual Scenario (BAU)
2. Aggressive Renewable Expansion (RES)
3. Renewable energy and aggressive expansion of hydro power (RES+Hydro)
4. Nuclear energy expansion (Nuclear)

Heavy reinforcement of transmission infrastructure in the NE region has been proposed in all the scenarios, due to the possible heavy expansion of large hydro capacities especially in RES+Hydro scenario. All single line systems at the 132 kV level in the north eastern part of NE region are reinforced with a double line system. The evolution of NTCs between BH, NP and the Indian power regions of ER, NE and NR are also carefully implemented based on the requirements.

A visual representation of the scenarios and a comparison of their dimensions can be seen in the Figure (67). The visualization clearly shows the direction of progress from a traditional market orientation to a liberalized market, all the while also describing the transition towards renewable energy. Due to several security, economic and social reasons, almost all large hydro capacities, and all nuclear power installations in the region are owned by the regional government companies. Therefore, it is quite understandable to consider scenarios defined with these technologies in mind, on the traditional market side of the development path. CCGT and clean coal technologies are now promoted throughout the region, and the amount of private investments in these technologies are considerably large. Furthermore, VRE installations are highly subsidized in the sub-continent region, and a significant number of private investments already exist. Hence, the CCGT and RES oriented scenarios are shown to lean more on the liberalized market side.

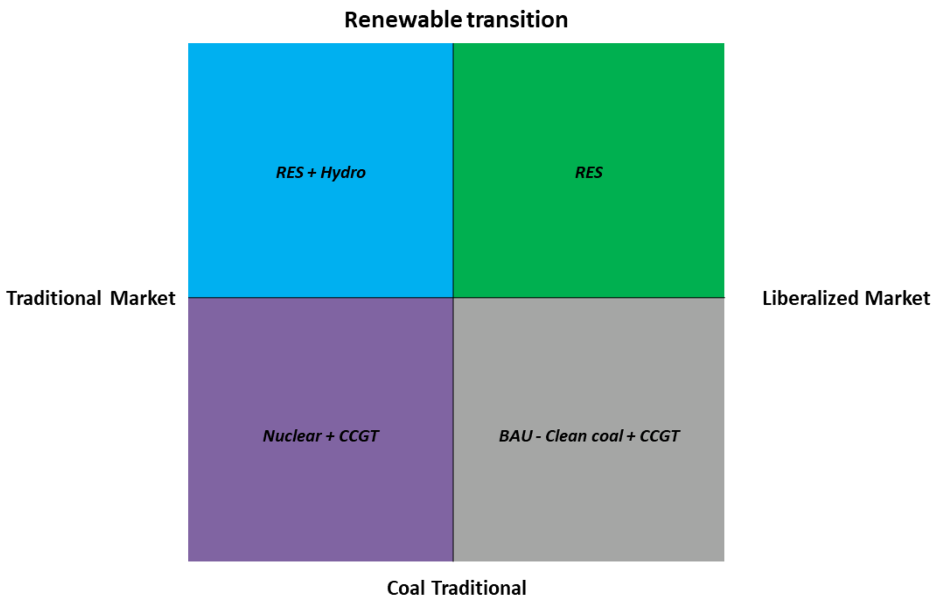


Figure (67) Definition of scenarios and their dimensions for the Indian sub-continent towards the target year 2050

5.2.1. Scenario 1: Business-As-Usual (BAU)

This scenario is closer to the discussed base scenario, where only the current policies proposed in the year 2014 and no new policies of the regions in the subcontinent considered, with only the change in growth of electricity demand. The major changes in comparison with the base scenario defined and simulated for validation of simulated results, would be the replacements of coal-fired power plants at the end of their lifetimes with a smaller CCGT capacities, and the implementation of 'clean' coal power plant technology. In this scenario, all the proposed coal- fired generation capacities in the Indian power regions after the year 2025 have been assumed to be 'clean' coal technology, with higher conversion efficiencies, considerably lower emissions output and larger capital costs defined. The overall installed capacity defined for the year 2050 in the scenario comes to around 450 GW, which is considerably lower than the RES centric scenarios defined later.

Other changes include the improvement of the transmission network till the year 2030, which is already included in the input data, based on the national strategy or the five-year network development plan of India. The building up of capacities in BH, NP and SL will also not have major changes than those which were already defined in the base case. However, in the BA region, a large amount of gas-fired capacity is added up, considering the availability of cheaper gas, and India is expected to continue importing electricity from flexible gas power plants to cover the peak and secondary loads. No provisions are given to the automatic refurbishments of VRE capacities like solar PV and wind energy, and the proposed offshore wind capacities in the specified development zones are not implemented.

This scenario highlights the probability of the sub-continent region unable to break its dependency on fossil fuel-fired electricity generation, which seems very realistic at the moment. The disabled automatic RES refurbishments are also a measure of the possibility of decrease in the interest over time by private investors due to financial decline.

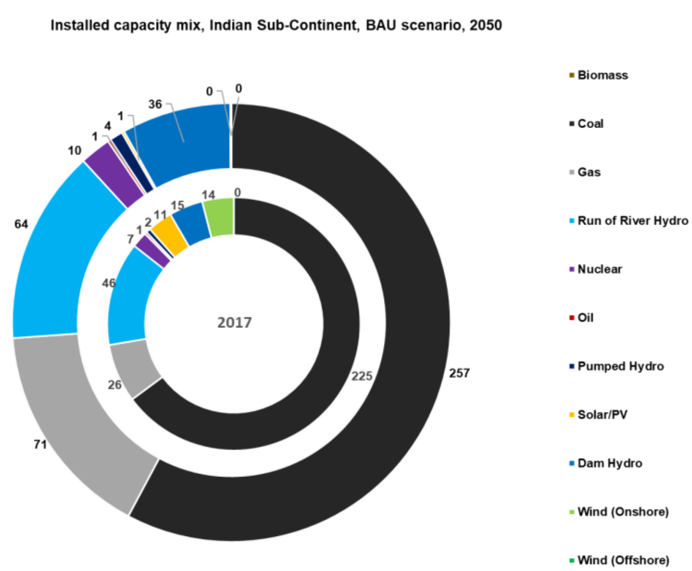


Figure (68) Installed capacity shares for the target year 2050 in BAU scenario, without RE refurbishments

5.2.2. Scenario 2: Aggressive Renewable Expansion - 'RES'

This scenario is designed around the ambitious plans of the GoI to increase renewable capacity to 175 GW by the year 2025, though a believable assumption of timeline extension and capacity addition has been considered. Large expansions of Solar PV capacities, in the NR, SR and WR regions, along with 5 GW of PV capacity expansion in the ER region has been included. All the planned expansions for onshore and offshore wind installations up to the year 2035 are considered, and several more have been planned at identified feed in nodes in the scope of this scenario. Provisions for automatic RES refurbishments have been made available in the simulation model, describing an increasing positive intent of private investments in RES capacity. Thus, this scenario has one of the highest installed capacities in the target year 2050 (around 520 GW), in comparison to all the discussed scenarios in this thesis.

This scenario however, does not completely discourage all types of conventional generation technologies, the addition of small capacities of gas-fired CCGT capacities near demand centers when deemed necessary are considered too. This is in terms with the strategy of implementing high flexibility and lower capital-intensive technologies to support a higher RES penetration in the electricity system. The fuel prices of all the conventional generation technology types are increased significantly in all scenarios, especially in the later years of the simulation timeline, promoting the electricity generation from RES sources. An overall increase of 122 GW of VRE capacity and around 15 GW of small hydro capacities (DRE) has been included in this scenario.

The concept of base load mentality is assumed to vanish, and the electricity sector is focused on covering the complete load. The national strategies are revised and no limitations to the addition of wind and PV are defined. Almost all planned hydro power capacities until 2030 in India have been integrated, excluding a few highly disputed dam hydro power plants in the NE and NR regions. All the proposed hydro power capacities in BH and NP regions are included. The short-term planned small hydro capacities in the NR, the SR and the WR regions are included until the year 2030, in lieu of the subsidies offered by the regional governments in the said regions. The improvement of pumped hydro storage capacities is also being considered, where several pumped hydro power plants are constructed in the mountainous regions of BH, NE and NP.

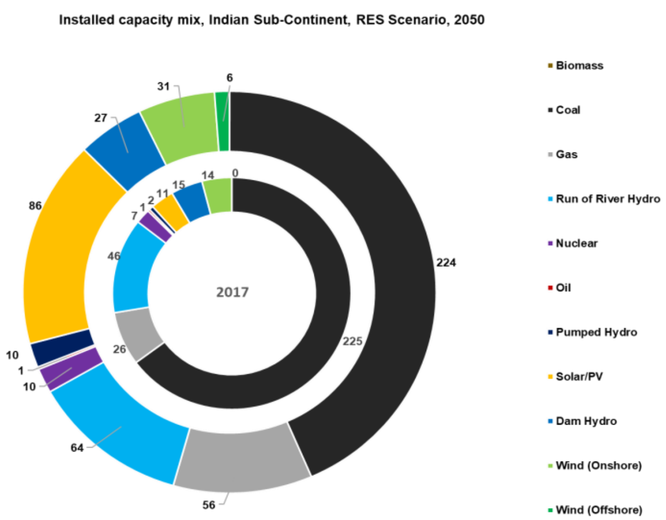


Figure (69) Installed capacity shares for the target year 2050 in RES scenario, with RE refurbishments

5.2.3. Scenario 3: Renewable Energy and expansion of Hydro power – 'RES+Hydro'

This scenario heavily focuses on the accelerated utilization of the hydro power potential, within India (esp. NE region), and also in regions like NP and BH. Over 50 GW of hydro power plant capacities, mainly run of river hydro power capacities, including a few dam hydro and pumped storage power capacities are installed in the above said regions. The scenario focuses on the effective integration of capital stock intensive carbon free generation capacities along with the purpose of utilizing the mountainous regions of BH, NE and NP, mainly for exploring options in pumped storage facilities. The scenario has an installed capacity of around 515 GW in the target year 2050, for the Indian subcontinent region. Automated RE capacity refurbishments in the scenario simulations are considered, as the scenario revolves around the strategy of increased priority on RES.

All delayed or cancelled hydro power plants are given priority and are added to the fleet with the start of the year 2020. The dam hydro power capacities deferred due to environmental concerns are all now assumed to be replaced by smaller run of river units adding up to the proposed capacity, thus reducing the ecological impact expected from building a dam. Coal-fired power plants, like with the other scenarios, are assumed to be replaced by smaller CCGT extensions at the end of their technical lifetimes. The Indian strategy of the expansion of hydro power plant capacities in NP and BH is the highlight of this scenario, with investments expected solely from India, based on mutual agreements of power plant ownerships and sharing of generated power. This is achieved in the model by adding the all the planned power plants proposed in this strategy by the governments of India, Bhutan and Nepal in to the installed capacity mix. New extensions of the National Hydro Power Company Limited (NHPCL) as regional companies in the BH and NP regions have been defined in the investors list. The expansion of VRE capacity in this scenario is not as vigorous as in the case of RES scenario, and is limited to around 90 GW. This is to chalk out an optimum penetration of VRE and DRE capacity in the electricity system of the Indian subcontinent. Offshore wind installations planned from the year 2030 are included, to encourage the VRE+DRE hybrid system solution. This scenario also evaluates the HVDC connections planned in the Indian regions, effectively connecting the VRE generation in the south with the DRE capacities in the north.

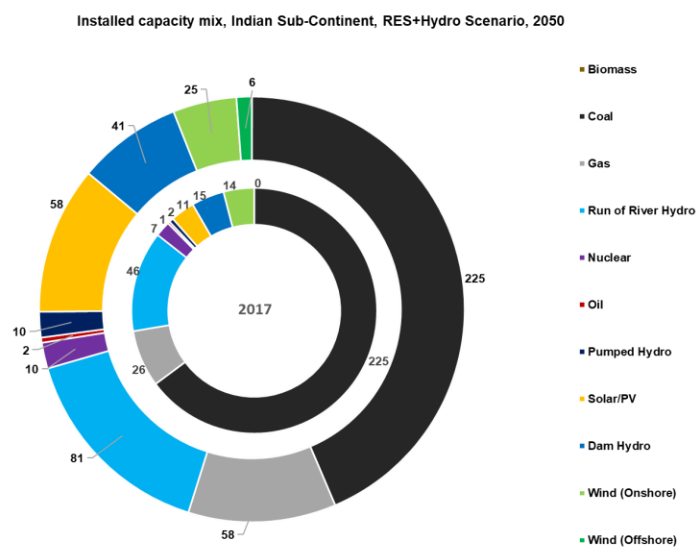


Figure (70) Installed capacity shares for the target year 2050 in RES+Hydro scenario, with RE refurbishments

5.2.4. Scenario 4: Nuclear Energy and Renewable Energy - Nuclear

The 'Nuclear' scenario brings highlight to the nuclear situation in the subcontinent. The nuclear energy targets of all the included regions are said to be successfully achieved by the year 2030. The use of Thorium HT- FBR technology in India is promoted, and a buildup of up to 28 GW of nuclear capacity distributed evenly among the Indian power regions have been considered. The regions of BA and SL get their first nuclear capacities successfully, further improving the covering of the electrical demand in the regions with less dependency on their prominent gas-fired capacities. However, all the already existing gas-fired capacities are assumed to be still active until their shutdown year. This assumption is made based on the fact that these two regions, especially the region BA exports cheap electricity from its gas fired capacities, to the Indian regions of ER and NE. The overall installed capacity in this scenario adds up to 455 GW, with prominent increase of nuclear capacities in the discussed regions. The automatic RES refurbishment provision is not made available in the scenario simulations, to highlight the effectiveness of the designed nuclear fleet.

New coal-fired capacities are not added after the year 2025, once the already installed capacities reach the end of their lifetimes. Most of the newer coal power plants in India, BA and SL still stay in operation till the end of the target simulation year, but the coal prices are made expensive to discourage the use of coal-based technology in the subcontinent. The renewable targets included in the national strategies of the regions (excluding the Indian power regions) are almost already achieved, with initial installed VRE capacities, along with the addition of small hydro capacities. This scenario also focuses on the building up the capital stock in specific model regions, thus requiring a heavy capital investment with every new capacity addition, but smaller depreciation values considering the large lifetimes of the hydro power plants and the nuclear power plants.

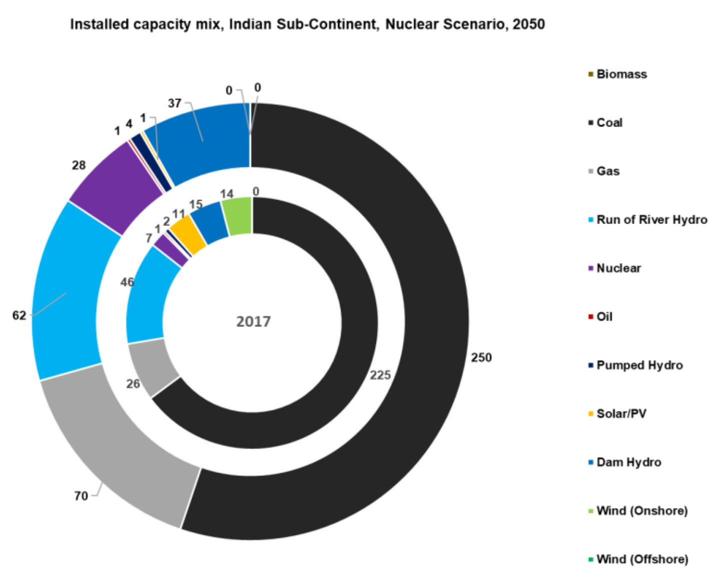


Figure (71) Installed capacity shares for the target year 2050 in Nuclear scenario, without RE refurbishments

5.2.4.1. The sustainability aspect of nuclear power technology

Nuclear power generation technologies are characterized with steady generation outputs and large reliabilities. However, they do not have the load following capacity and the flexibility of supply like the coal-fired and gas-fired technologies. A large amount of research is now upon the enhancement of the load following capability of nuclear power generation technologies, as nuclear power could most likely be a valid replacement for conventional carbon intensive thermal power generation technologies. Though nuclear power plays a significant role in many low-carbon scenario studies, several aspects of nuclear power have to be analysed mainly in terms of sustainability and economics.

The incompatibility of nuclear power and flow based renewable power (solar PV, wind, hydro power) is evaluated to be stronger in terms of economics and sustainability, than in technical operability [60]. Nuclear power plants tend to be more expensive in the long run, in comparison to various other alternative generation technologies. Both renewable and nuclear power supplies are found to be characterized by individual inflexibilities, different in nature and with different reasons. Studies also suggest both nuclear power and flow renewable power claim the same base load area when operating in the same system even while they serve separate power loads. Both technologies are observed to request add-on services from flexible power supply like coal- and gas-fired power plants, or more recent options like load management and battery storage, in compensation of their specific inflexibilities.

Furthermore, an assessment on nineteen different criteria concluded that nuclear fission technology is not a sustainable technology [61], especially on the long run. With several other discussed factors like proliferation, safety and waste disposal, nuclear power doesn't seem to be a great option for the sustainable transition to carbon free generation in the Indian subcontinent region. However, as several subcontinent countries already have concrete plans for nuclear capacity expansions planned in the coming decade, and for the natural curiosity of how the system behaviour would change, a scenario based on aggressive nuclear capacity expansion in the region is also considered in this thesis.

5.3. Capital stock calculations for capital stock intensive scenario

Capital stock calculations for power plant assets defined in the RES+Hydro scenario are also calculated, to get a measure of the 'wealth' of each power region. Calculations of the GCS and NCS for model regions are made, to relatively compare their capital stocks in the capital stock intensive scenario. All hydro power plant types have huge economic and technical lifetimes, so it makes sense to evaluate the capital stocks in a scenario centred around the expansion of this power plant technology type.

The comparisons of needed investments, resulting depreciation values, and evaluation of the possibility of the overall welfare in the region is the goal of such an analysis. This overall comparison of the increase in the GCS and NCS in all the regions helps us to get a bird's eye view of the major capital assets of the subcontinent power plant fleet.

The Figure (72) provides us with an overview of the investment required over time, showing large scale investments in the 2020, 2025, 2030 and 2035 in Hydro power plants. The investments in conventional power plant capacities seemingly decrease towards the end of the simulation timeline, due to improved interest in RE and Hydro power investments, an as no lifetime extensions for coal-fired capacities have been assumed. The blips in the thermal capacity investments are due to subsequent replacement of coal fired capacities with CCGT capacities in these years.

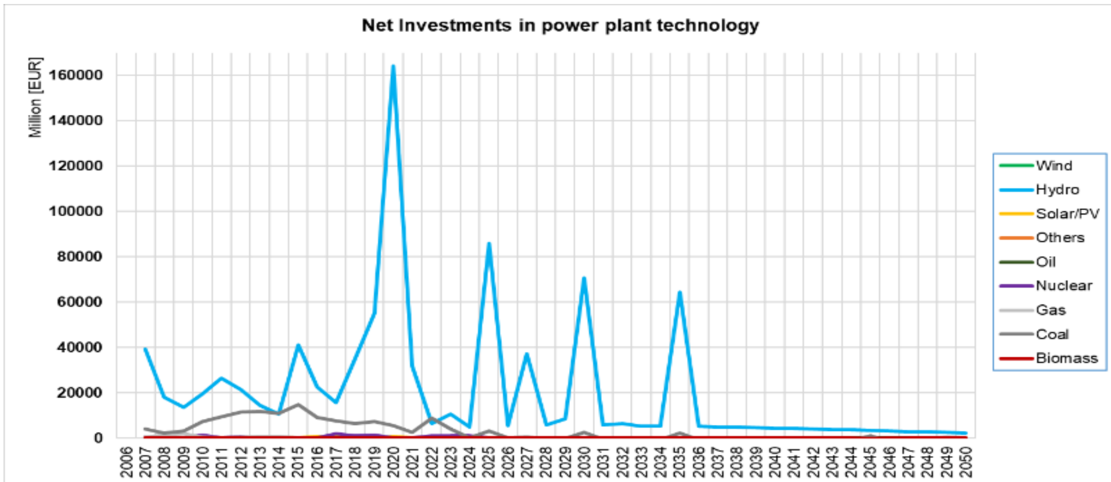


Figure (72) Investments over the years in the Indian subcontinent region

5.4. Model Validation

The validation of the input data in ATLANTIS_India has been done with respect to power plant input data of the BAU scenario for the Indian region. Other regions like BA, BH, NP and SL have been also integrated separately, as the inconsistencies in the available opensource data was quite high. The power plant input data for these regions have been done through several governmental reports (irregular) and news articles, which was a complex and a tedious process. However, it was taken care that most of the important installed capacities were integrated successfully in the overall power plant input data for the above said regions.

The installed capacities as per the input data in ATLANTIS_India for the Indian region can be seen as illustrated in the Figure (63). The validation was done by comparing data with actual reports published as yearly reports by the MoP, GoI [3][20]. This input data was initially used to run a scenario without the inclusion of BA, BH, NP and SL, and the generated electrical energy by technology types was compared again with the MoP reports.

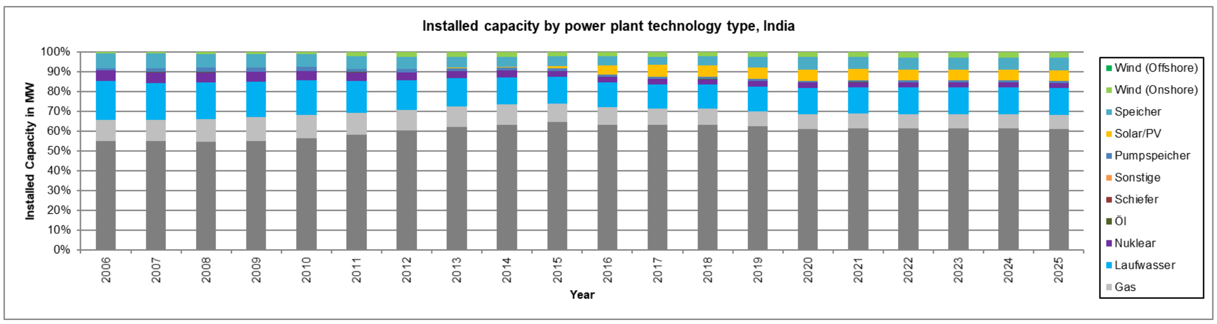


Figure (63) Model validation, installed capacity shares in the Indian region defined in ATLANTIS_India

In the simulated year 2019, the total installed capacity in the Indian power regions was found to be 333 GW, with subsequent capacity addition from a total 180 GW in 2006 till the year 2018. The amount of coal-fired capacity in the capacity mix in the year 2019 was ascertained to be 210 GW, which is close to actual values by the reports from the MoP. The other capacities of gas-fired (29 GW), run of river hydro (40 GW), dam hydro (17 GW), pumped hydro storage (3 GW) and nuclear (7 GW) are also close to the published values. The installed capacities of other RES (wind and solar PV) amounts to 27 GW instead of 35 GW, and falls short of the published results, especially due to inconsistencies in available data.

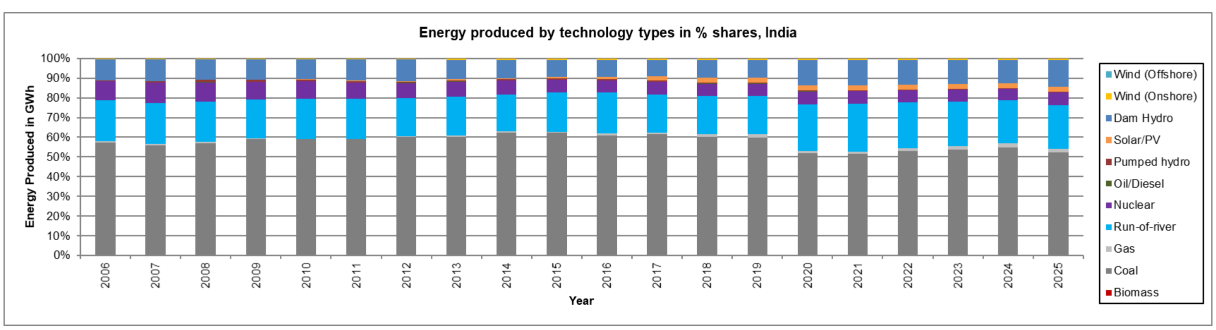


Figure (64) Model Validation, Electrical energy generated by technology shares in ATLANTIS_India, for the Indian power regions.

The electrical energy generated by technology types in ATLANTIS_India is as shown in the Figure (64). It can be seen that the 60 percent share of coal fired generation is quite less compared to the 67 percent as seen in the reports, especially in the years 2006-2014. The main cause for this difference is the utilization factors used for power plant definition. Hydro power plants in ATLANTIS_India were defined with higher operating hours, and at higher utilization factors than the coal-fired generation capacities. Coal-fired capacities in the Indian electricity sector are run with higher utilization factors of 87 percent, while in ATLANTIS_India, around 70 percent utilization factor is defined. Also, the consideration of the weather dependent run-of-river hydro availability also brings in some uncertainties, as a single weather pattern for each region was defined, and the specific resource availability was defined for such power plants. Thus, the generation for run of river hydro capacities in the model is a bit higher than expected, while the coal fired generation falls shorter than actual values.

The validation of the model for the simulation year 2019 was successfully completed and the input data up to the year 2017 was thoroughly checked. The assumptions made in the course of validation are of course important, and were made mainly for the sake of the reduction in complexity of futuristic simulations, with an expected high share of weather dependent generation technologies in the capacity mix.

CHAPTER 4

Scenario Simulation Results

6. Results

6.1. Scenario 1 results: BAU

This scenario is based on the current energy policies (2014) of implementing 'clean' coal-fired capacity additions and CCGT replacement of old coal power plants at the end of their technical lifetimes. This scenario focuses on the integration of around 70 GW of VRE technologies like solar PV and Wind, around 20 GW hydro power (both run of river and dam hydro together) and 4 GW of planned nuclear capacity expansion, without giving any thought to losing the coal dependency.

With the new regulations for coal mining, coal (both imported and domestic) still remains a cheap option both with regards to fuel prices and technology, and all planned expansions of coal-fired capacities in the subcontinent is considered. Thus, a large share of coal fired capacities can be expected in this scenario. The Figure (73) shows the installed capacity share in the electricity system of the subcontinent region, both in MW and in percentage share of the total installed capacity in the model.

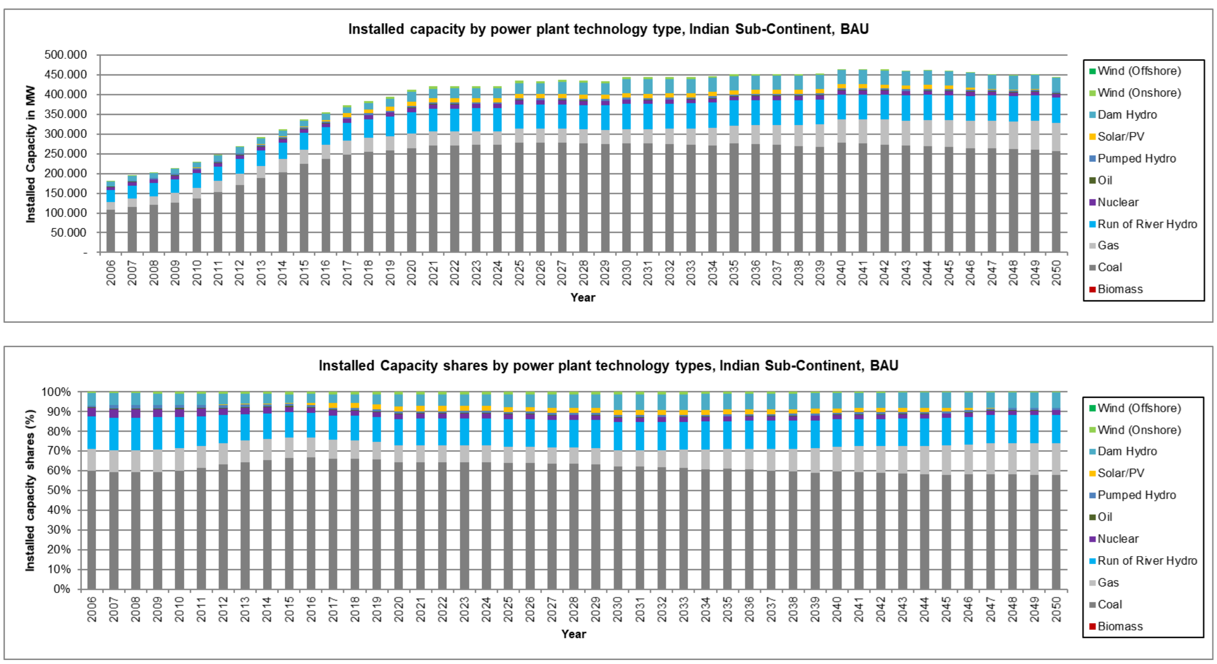
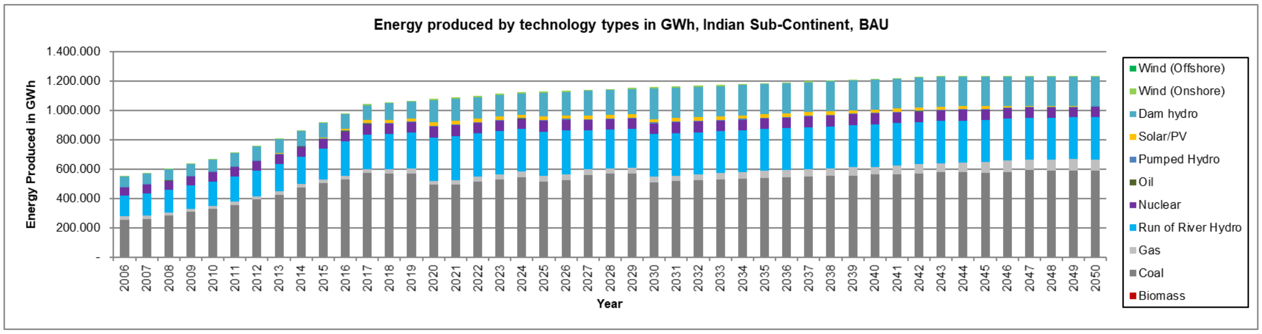


Figure (73) Share of installed capacities in the total power plant capacity mix, as defined in the BAU scenario for the Indian Sub-continent region

The comparison of the simulated energy generated by each technology type and their respective share in the installed capacity mix gives us an overall evaluation of the effectiveness of the specific technology type. With this in consideration, the Figure (74) illustrates the resulting electrical energy generated by each technology type in the BAU scenario, along with their shares in the overall electrical energy mix.



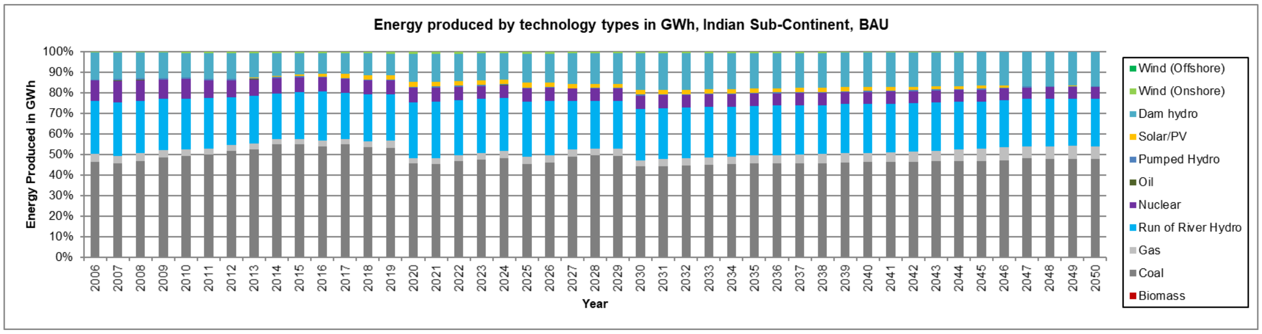


Figure (74) Electrical energy generated by each power plant type, in the BAU scenario for the region ATLANTIS_India, in GWh and in percentage shares.

It can be observed that the share of coal fired technologies still chips in a major share of the electrical energy generated, throughout the scenario timeline. The CCGT replacements commissioned in the place of old coal power plants also fulfill their role in filling up the gap created by the coal fired generated capacities once they are shutdown. The share of electrical energy generated by run of river capacities relatively decreases, but the share of dam hydro power, with still almost no changes in installed capacity, the share of power generated increases.

The share of energy generated from nuclear capacities remain almost constant, even with almost a doubling of the installed nuclear capacity. The share of energy generated by the solar PV and wind capacity installations are significantly minor, and since refurbishments are not planned in the scope of this scenario, their shares vanish completely in the year 2047. A look at the yearly change in the specific electrical energy generated by installed technology types shed more light on the scenario situation. The Figure (75) illustrates the yearly changes in electrical energy generated by several technology types.

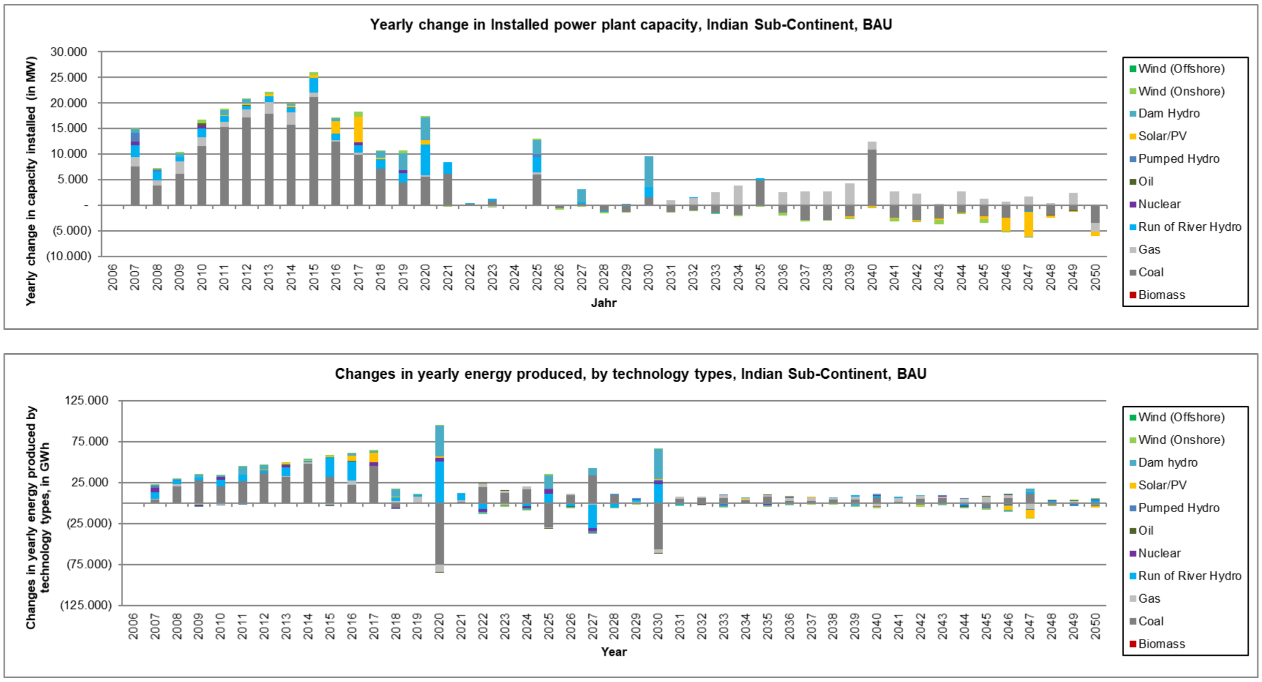


Figure (75) Yearly changes in installed capacity (above) and the electrical energy generated in GWh (below) by different power plant types, Indian subcontinent, BAU scenario

The resulting simulated load flows in the system from the in the RDZP market model simulations can be visualised with the help of the tool ATLANTIS VISU 2.0 as shown in the Figure (76) below. Over-loading (dark red) of the transmission line and its size determines the bottleneck situation in the region, and the direction of load flow (arrow head) determines whether the import or export from a certain region takes place. The Figure (76) illustrates the load flows in the transmission network of the electricity system in the Indian subcontinent, in the month of August at peak 'a' period in the year 2050. The specific period is chosen for analysis, as it forms part of the highest electrical load in the year, in the subcontinent region.

It can be observed that there are large transmission bottlenecks, especially in the cross-border region between the regions NR and WR, as new clean coal -fired and CCGT capacities export a large electricity from the region NR to WR. These bottlenecks could be the main reason for a reduced generation from new coal-fired capacities, as other older and CCGT capacities are found to compensate during redispatch. The bottlenecks observed in the BH and NE regions is due to the aging and insufficient 132 kV transmission infrastructure, and due to the fact that many of the larger hydro power plants go online after the year 2030 in both regions. The NP region can be seen to accommodate the load flow between NR and ER region, by forming a closed transmission ring. The 'electrical highway' project in the NP region, expected to be completed by the year 2030, is a 220 kV high voltage transmission line system is seen to be really effective in managing the load flows around the region. This gives ER the possibility to import cheap electricity from hydro power from the NR and NP regions respectively, and most of the expensive coal-fired electricity generated in the ER region is seen to be exported to the regions SR and WR.

The availability of better and younger transmission infrastructure in the SR and the WR regions, greatly influence the situation that these regions can effectively import electricity from the ER and NR regions, without a requirement for reinforcement of the transmission grid. The proposed interconnection of the ER and NE regions through the BA region by building cross border capacities on either side of the BA region does not seem to be effective as the transmission lines from ER to NE around the BA region are highly loaded. However, due to import, the interconnection between BA and NE seems to be heavily loaded.

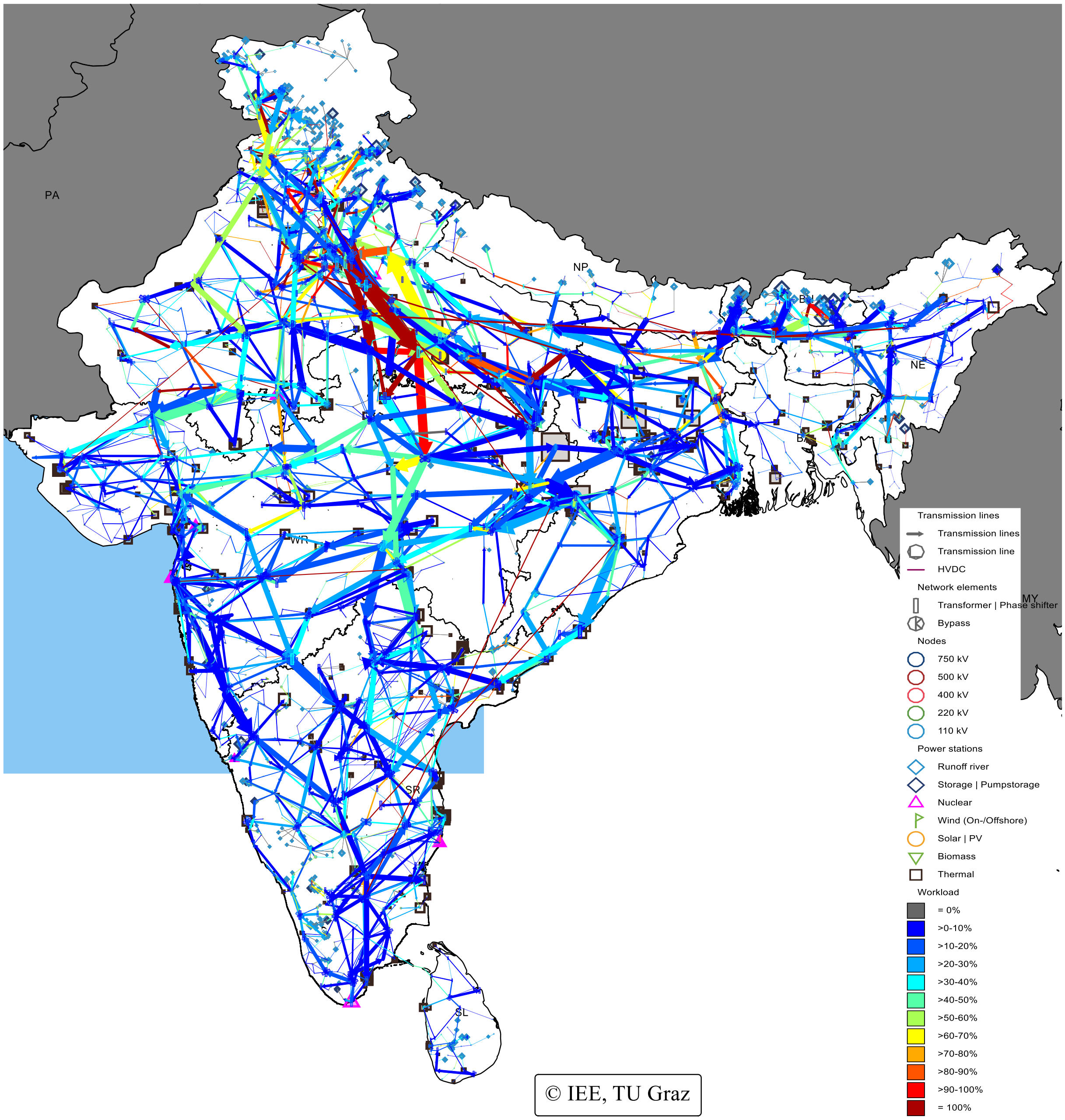


Figure (76) Load flow visualization of the transmission network resulting from redispatch in the BAU scenario, August Peak ‘A’ period, 2050

As explained in the market model definition, redispatch can be either regional or interregional, depending on the transmission infrastructure and direction of the load flow. Due to the redispatch, several power plants have to compensate by increasing or with-holding their generation capabilities to manage the power transmission in a better way. In this scenario, positive differences in electrical energy generated due to redispatch (positive redispatch) can be seen in coal fired capacities, gas fired capacities and a few of the dam hydro capacities which work towards compensating the decreased generation (negative redispatch) from other generating capacities due to transmission bottlenecks. Coal fired capacities have a major task of not only providing for the base load in this scenario, but also to significantly compensate for transmission bottlenecks in the Indian subcontinent in the region. Few of the dam hydro power capacities help out too, be compensating for the transmission bottlenecks especially around the BH and the NP regions respectively.

However, the generation from run of river capacities take a considerable hit, they generate less even with high utilization factors defined in the input data mainly due to the limited transmission capacities between the generating capacities and demand centres. It makes definite sense as several hydro power capacities in India are usually located in isolated mountainous regions, far away from the residential and industrial demand centres. With limited transmission connectivity, these power plants cannot be easily and effectively integrated in to the grid, and it results in coal and gas fired capacities compensating the situation. Gas fired capacities, in India, are usually located very close to the demand centres and provide large flexibilities to the regional system, thus compensation in case of negative redispatch due to transmission bottlenecks can be easily carried out. The Figure (77) provides an illustration of the increased electrical energy generated or withheld by specific technology types in the scenario to accommodate positive or negative redispatch respectively.

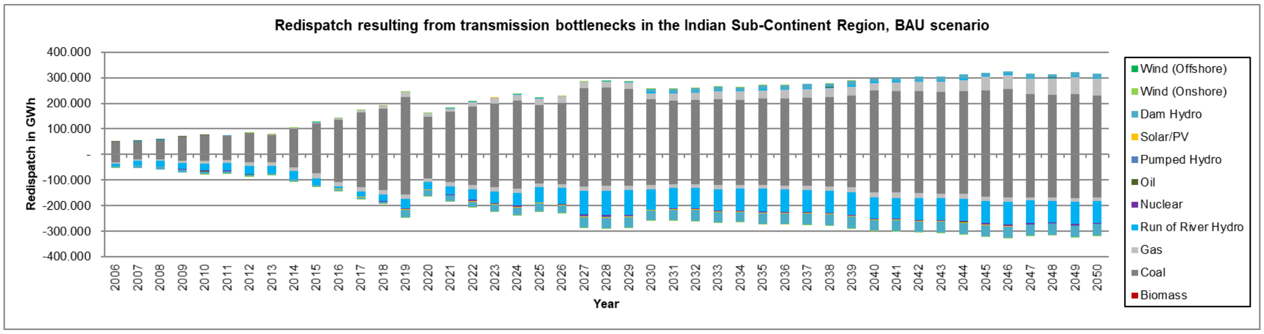


Figure (77) Redispatch in power plant generation resulting from transmission bottlenecks in the Indian Sub-Continent region, BAU scenario

A Figure (78) gives us a clear understanding of where the positive and negative redispatches occur, and how the various different power plant capacities have to compensate the bottlenecks around each region. It can be seen that the thermal power plants (coal and gas-fired capacities) in the NR and ER regions have to majorly compensate the reduced generation in the WR region due to the several bottlenecks in the SR-WR region and major transmission bottlenecks in the cross-border lines between the WR, NR and ER regions.

The thermal capacities in the region SR have also a reduced generation due to the bottlenecks between the capacities and demand centres. From the load flow visualization, several bottlenecks, especially in the 220 kV transmission level, are observed around the Bangalore and Chennai area. The hydro power plants in the northern part of the ER and in the region BH are constrained with limited transmission capacities, especially the long-term planned large capacity expansions in the said region after the year 2030. Thus, it becomes a focal point for the TSOs to improve the transmission infrastructure adequately in the region for the effective integration of these long term planned capacities. Furthermore, several power plant capacities in the NE region are observed to have a positive redispatch differences, concerning the transmission bottlenecks observed mostly within the region, and also across the regions BA, BH and NE.

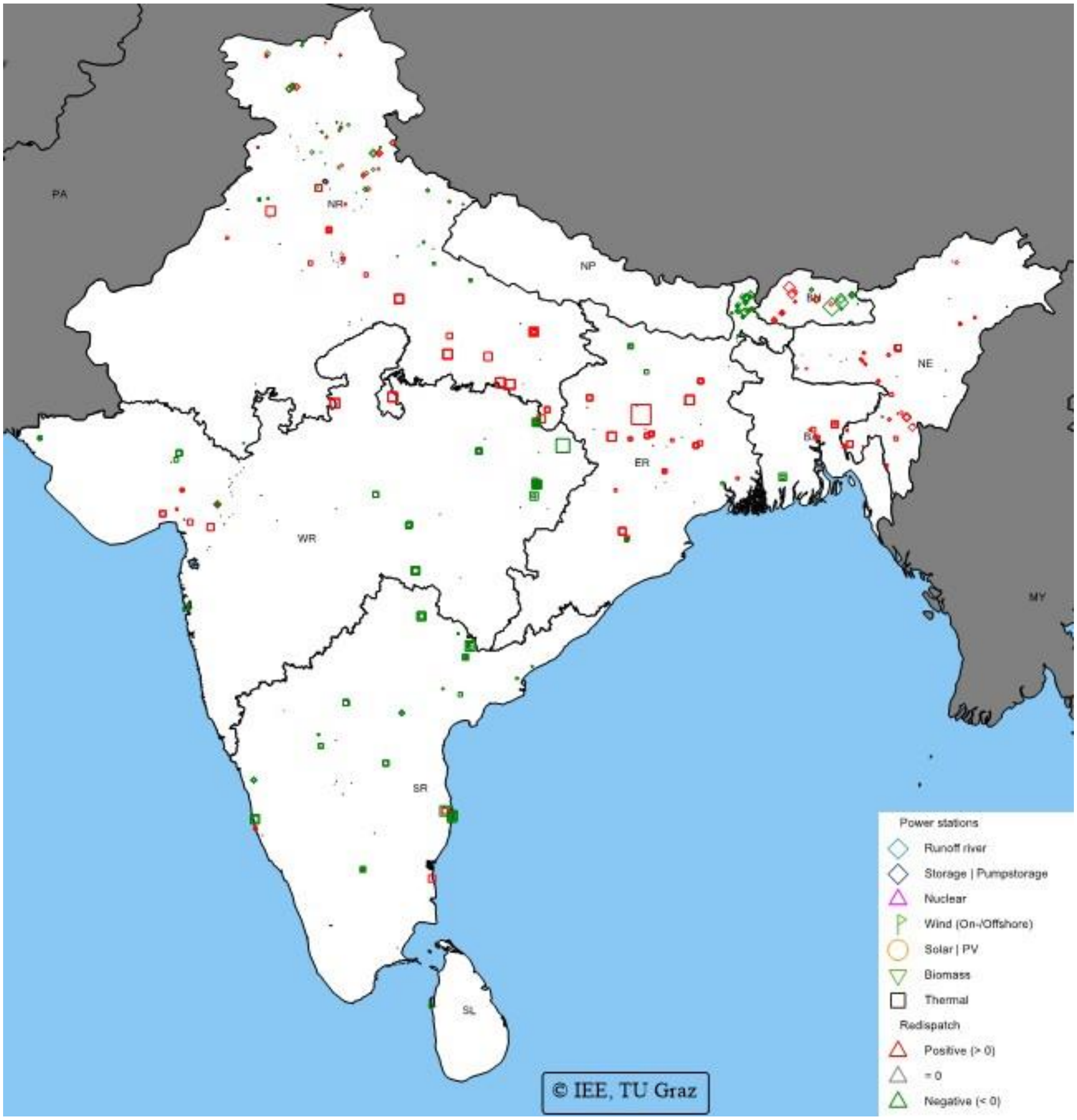
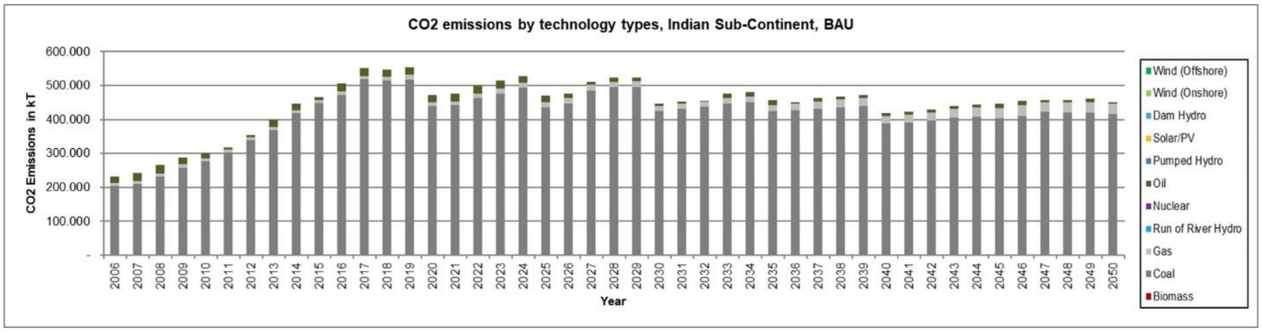


Figure (78) Geographical visualization of positive and negative redispatch in power plant generation, BAU scenario, August Peak ‚a‘ period 2050 in comparison with August Peak ‚a‘ period 2049

In lieu of India's commitment towards reduction of emission intensity of its energy sector, the evolution of CO_2 emissions resulting from electricity generated are also studied. This scenario, for obvious reasons, has the highest observable emissions in comparison with all the defined scenarios. The overall CO_2 emissions resulting from the power plant fleet in the Indian sub-continent is found to be around 450 Million Tonnes of CO_2. This is relatively lower than projections by many BAU studies [62]. The significantly lower values could be attributed to the integration of 'clean coal' technologies, and highly efficient CCGT replacements, which are defined with significantly lower emission intensities in the scope of the model. The Figure (79) gives us a representation of the CO_2 emissions calculated due to electricity generation by the power plant fleet in the Indian subcontinent region, and its development over the years till the target year 2050.

With every coal power plant capacity going offline, there are significant reductions in emissions observed, and a subsequent increase in emissions follow due to the subsequent CCGT replacements and the addition of additional capacities of clean coal power plants. The decreasing share of CO_2 emissions from coal-fired technologies show a tendency to decrease while the gap is filled up by emissions from the CCGT expansions in the region. The share of oil-fired technologies in the emissions decrease considerably, as all oil power plants are assumed to be inactive after their technical lifetimes have been achieved.



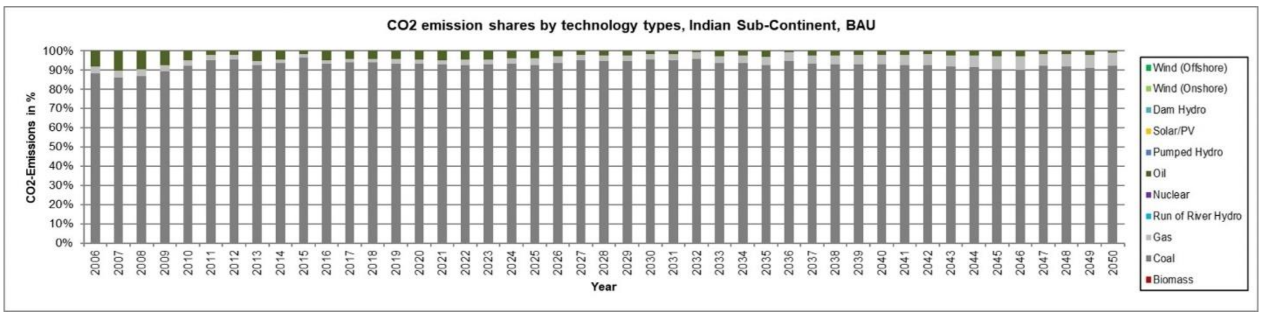


Figure (79) CO2 emissions resulting from various power plant technology types, BAU Scenario by the Indian subcontinent power plant fleet, 2006-2050, in kilo Tonnes and in percentage share

The prices observed in the model regions are basically related to the prices of fuel as defined in the input data. The fuel price evolution follows a steep curve until a certain limit is reached, and then is assumed to stagnate. For most of the fuel types, the saturation is assumed to occur sometime around the latter half of the 2040 decade. A Figure (80) shows the evolution of zonal pries in various regions, as calculated with the RDZP market model in the BAU scenario.

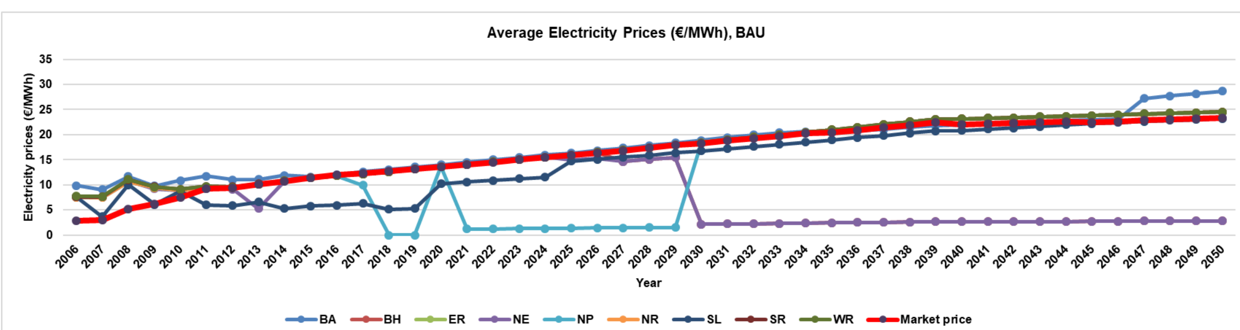


Figure (80) Market price evolution in the zonal pricing of various model regions, 2050, BAU scenario.

The zonal prices in almost all regions follow the average market price evolution in the overall regional market, except the regions of NE, NP and SL. The NE region follows the average market price until the year 2030, and a drastic reduction in zonal price is observed due to the addition of several run of river hydro power plant capacities along with the improvement of infrastructure between NE and ER, BH and BA regions. The improvement in cross border capacity between the regions is highly effective as a large amount of load flows occurs between these regions and other larger demand-rich regions. The prices in NP increases whenever there is addition of diesel generation capacities and the price for diesel defined for NP is relatively higher than in other regions due to reasons of availability. The SL region initially has a lower price, but eventually catches up the average market price once the interconnection between SL and SR is established, in the form of a HVDC line in 2025.

6.2. Scenario 2 results: RES

The RES scenario focuses on a large increase in RES capacities at planned and determined locations throughout the model region of ATLANTIS_India. The solar PV and wind capacity expansions are carried out at existing feed-in points and at locations showing considerable potential (c)(u). The results of this scenario focus on the effectiveness of the increased capacity expansions of solar PV and wind (both offshore and onshore) in the Indian subcontinent region. As discussed in the scenario definition, the addition of large capacities of solar PV and wind have been carried out at the regions of NR, SR and WR respectively, along with offshore wind installations in the specially designated offshore wind zones in the regions SR and WR. A smaller increase of PV and wind capacities are also done in the region of ER, where it is observed that a substantial potential exists, though no capacities are proposed in the GoI plans. The overall addition of VRE capacities bring in about 120 GW of renewable capacity in the Indian power plant mix by the year 2050.

To effectively analyse such a strategy, the regional analysis of the installed capacities and the produced energies also become important. The regional effectiveness of the RE capacity expansion will be discussed later in the 'Discussions' chapter. However, as in the case of other scenarios, an overall comparison is initially made to ascertain the overall effectiveness of the added capacities. The Figure (81) shows the installed capacities by technology shares for the overall model region.

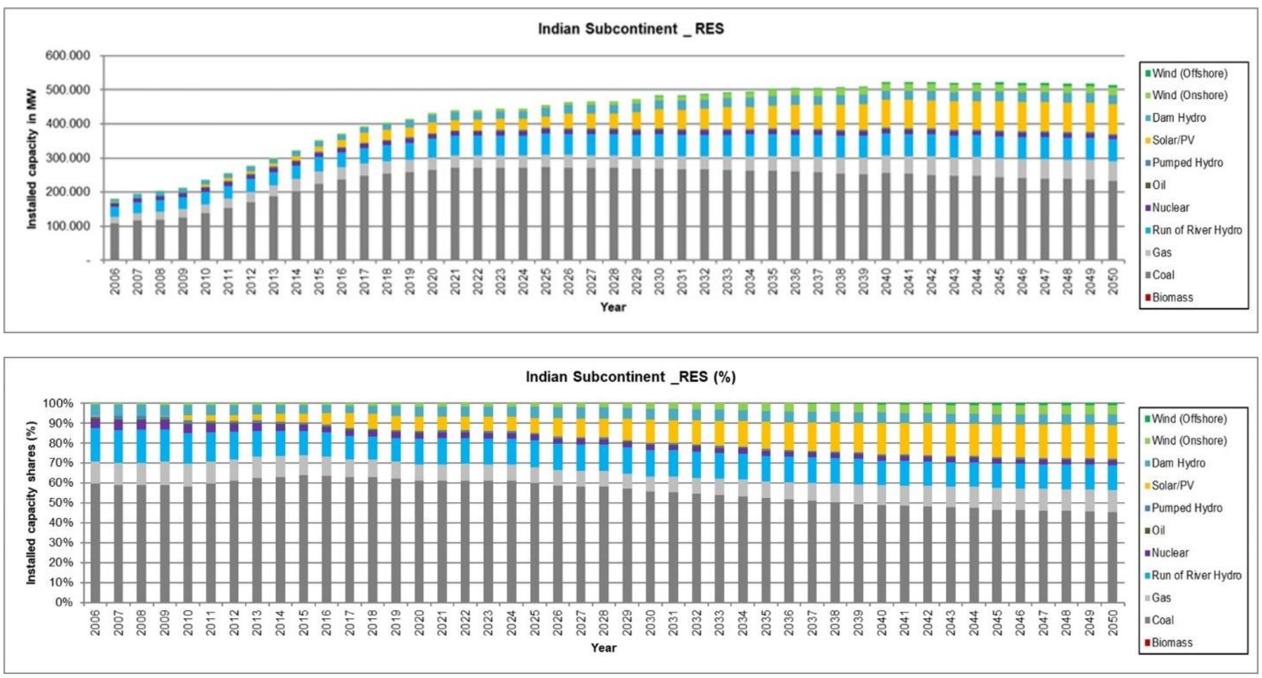
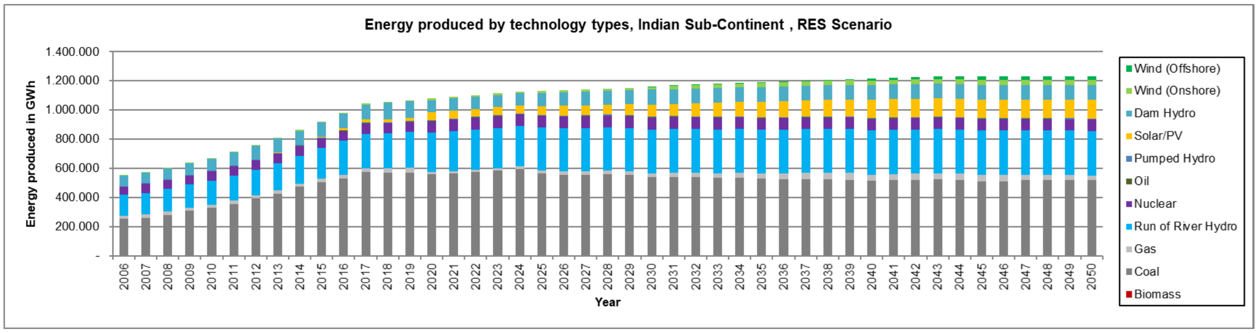


Figure (81) Installed power plant capacities by technology shares in the RES Scenario, Indian subcontinent energy system

A brief comparison with the total amount of energy produced by each technology type highlights the effectiveness of the capacities of each technology types installed. The Figure (82) gives a representation of the total amount of energy produced by each technology types installed in the scenario, as described in the scenario definition.



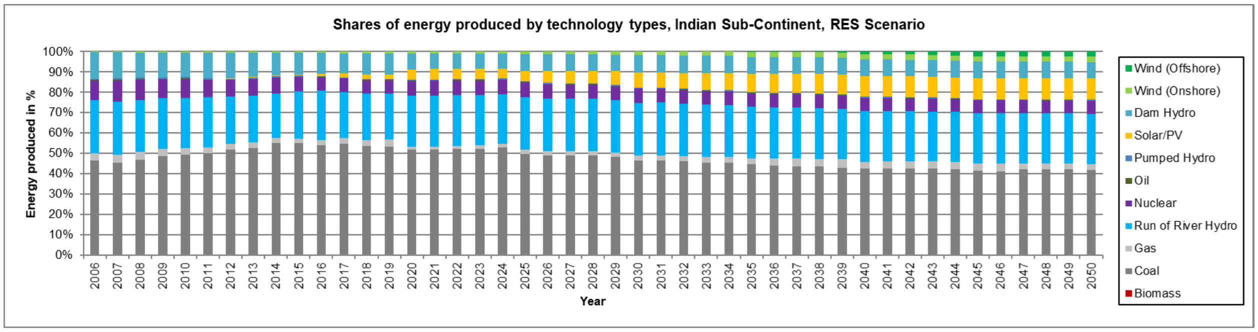


Figure (82) Energy produced by each technology types in ATLANTIS_India, RES scenario, in GWh and by percentage shares.

Initial observations made from comparing the installed capacities and energy produced leads to an understanding that the generation from solar PV installations are not as effective as previously thought of, due to various reasons discussed later. However, the wind capacities installed show a nice increase in the energy produced by wind, and the effectiveness of the small 5 GW of offshore wind energy expansion in the development zones in the SR and the WR is seen to be high.

Regarding the solar PV expansions, a regional impact is clearly observed, rather at a system level. This could be due to the centralized additions in a few regions, and transmission bottlenecks resulting in redispatch of power generated. Solar PV manages to increase its share of energy produced from around 5 percent in the year 2014 to 16 percent in the year 2050, while energy produced by wind increases from 2 percent in the year 2014 to 9 percent in the year 2050. Coal-fired capacities eventually are replaced by smaller CCGT expansions, so energy produced from coal is observed to drop from around 60 percent in 2014 to 40 percent in 2050. The CCGT expansions, along with the help of the increased share of energy produced from RES capacities, fill up the gap observed from the decreased energy produced from coal-fired power plant capacities in the year 2050. A detailed overview of the changes observed in the installed capacities and the share of energy produced by each technology can also be observed in the following Figure (83).

The first increase of installed capacity and the subsequent electrical energy generated by solar PV and wind is observed immediately after the implementation of capacity expansions in the year 2010, and a larger increase in 2015-2017 is seen, showcasing India's commitment towards its agreement of the COP 21 and the SDG 2030 directives. A much larger change in the share of electricity generated is then observed in the year 2019, where the energy production by coal-based capacities reduce considerably due to new nuclear and hydro power capacity additions. The small expansions of offshore wind energy seem to be really useful, showing a larger than expected generation in the years 2040 and 2045 respectively. Further down the timeline, a gradual increase in the energy generated by solar PV and wind capacities and subsequent gradual reductions in the energy produced by coal-based capacities can be observed.

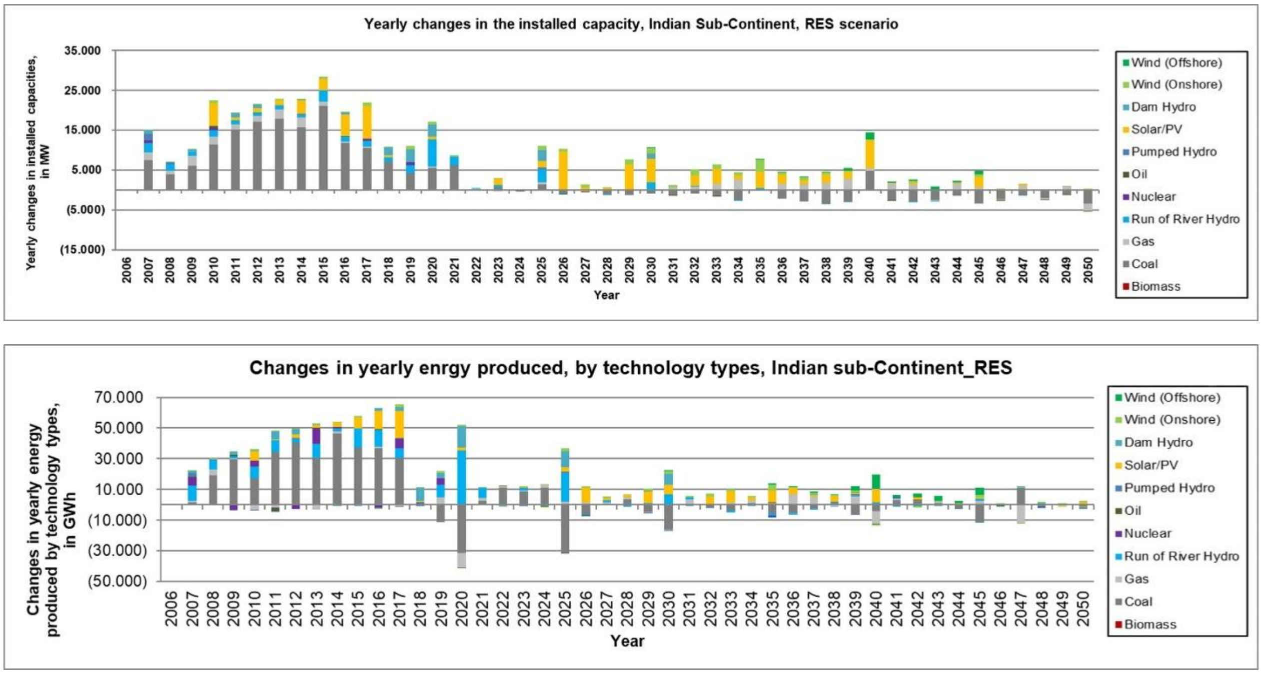


Figure (83) Yearly changes in the installed capacity (above) and the energy generated (below) by each technology type in the RES scenario

The simulated load flows in the transmission system are visualised, and the bottlenecks in the transmission system are easily identified. A representation of the load flows in the transmission network, resulting from the RDZP simulations for the month of August, and Peak ‘a’ period in the year 2050 is as shown in the following Figure (84). Several critical bottlenecks can be identified, based on their respective ‘loading’ levels. These critical bottlenecks can be seen in the NR, NE and NP regions, mainly due to the increase of solar PV and wind capacities in NR (west of NR region), and hydro power expansions in NE and NP. The severe bottleneck situation in the NR-WR direction, also observed in the BAU case, seem to be increasingly congested in the RES scenario. The generation from additional RES capacities planned in the NR and WR regions plays its part, even with reduced capacities of coal-fired plants in the said regions.

Even with a substantial reinforcement of the grid in the NE region from the year 2045, several transmission bottlenecks are observed in the north eastern part of the NE region where several large hydro power installations are proposed in the long-term timeframe. Also, the completion of the ‘Electrical Highway’ in the NP region, a 220 kV network reinforcing the overall transmission system around the region, proves to be a valuable asset as all bottlenecks surrounding the region of NP seemingly appear to be less congested (in comparison with the 2014 load flows (Figure (85)). This is clear from the fact that most of the run of river hydro and solar PV capacities in the ER region is planned in the region surrounding this electrical highway, and several transmission congestions in the region was expected.

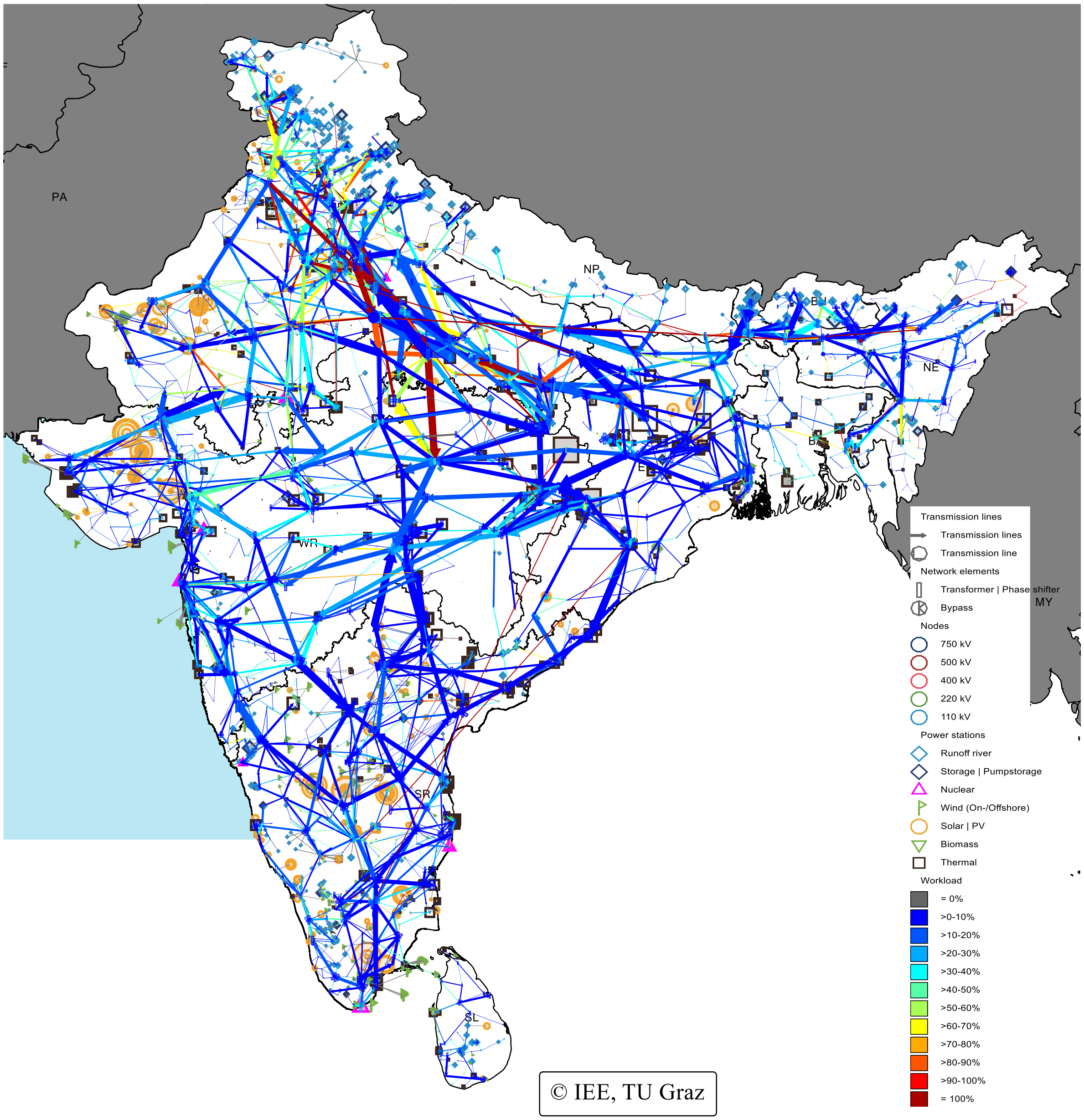


Figure (84) Load flows resulting from reispatch in the RES Scenario, simulation year 2050, August Peak ‘a’ period.

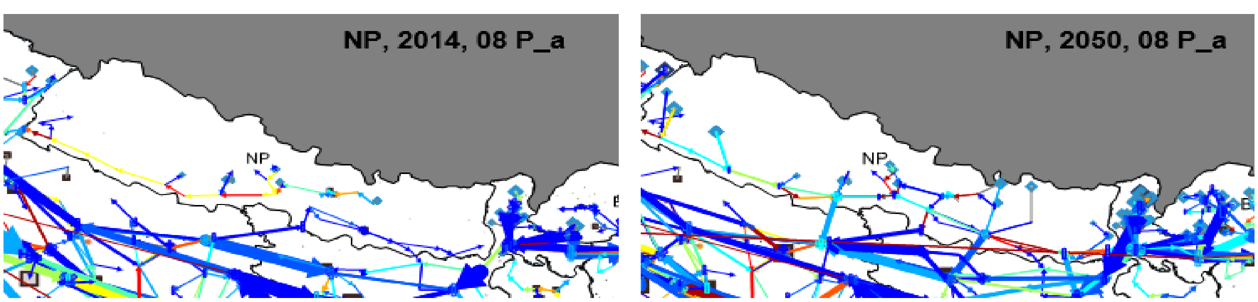


Figure (85) Effectiveness of the 220 kV new transmission infrastructure in the NP region, RES Scenario

Smaller bottlenecks in the SR and WR regions are also observed, especially around the feed-in nodes of the newly added solar PV and wind capacities. The observed bottlenecks can be cleared by reinforcing the transmission connectivity of the 220 kV network around these feed- in nodes. The recently added transmission infrastructure in the SR region seem to manage the power flows resulting from an increased generation from capacities in the region.

The differences in generation from powerplants due to redispatch resulting from the overall bottleneck situation within the transmission network in the Indian subcontinent gives us a clear indication of which power plant types have increased or with-held generation to manage power transfer around the transmission bottlenecks existing in the region and between model regions. A Figure (86) shows the changes in generation (positive or negative) resulting from power plant compensation towards redispatch across transmission bottlenecks in the system.

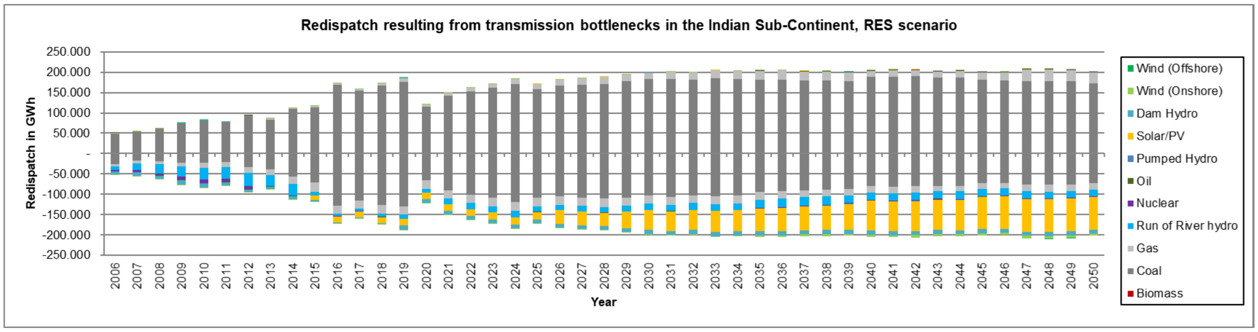


Figure (86) Positive and negative redispatch of installed capacities of different technology types, RES scenario resulting due to bottlenecks in the transmission system, in the year 2050

Coal-fired and gas-fired generation capacities show a large positive redispatch difference, considering their locations closer to the demand centres than other VRE and hydro power capacities. A few run-of-river hydro power plants and a majority of the VRE capacities show decreased generation due to the congestion created by limited transmission capacities within the region. This would lead to the conclusion that before a large-scale expansion of VRE and run of river hydro capacities is implemented, the transmission network around the feed in points of the proposed capacities have to be reinforced, for an effective integration. Interestingly, the negative redispatch situation from VRE capacities occurs from the year 2015, with the initial expansion of large solar PV capacities in the SR and WR regions.

The negative redispatch differences in the majority of run-of river hydro capacities could be a result of the significant bottlenecks observed in the NE, NP and BH regions, where the interconnecting cross border transmission facilities are severely loaded. The Figure (87) shows a map giving a geographical representation of the positive and negative redispatch differences occurring in several generation capacities due to transmission congestion.

An overview of the comparison of electrical energy generated by power plants resulting due to redispatch market simulation in the years 2050 and 2049 shows a large amount of coal and gas fired capacities, especially in the region of WR compensating the reduced generation from VRE technologies in the WR and coal fired capacities in the ER and NR region. This is almost exactly the opposite of the observations in the BAU scenario, hence the VRE expansion creates a major difference in the load flows in the transmission network. The critical bottlenecks in the NR region observed from the visualization of the load flows cause decreased generation in several power plants in the region. The NE region also has to compensate the decreased generation from coal-fired capacities in BA region, with its coal-fired and gas-fired fleet due to bottlenecks between the NE, ER and BA regions. The southern region shows that the VRE capacities have increased generation for redispatch compensation for reduced generation from many small hydro capacities.

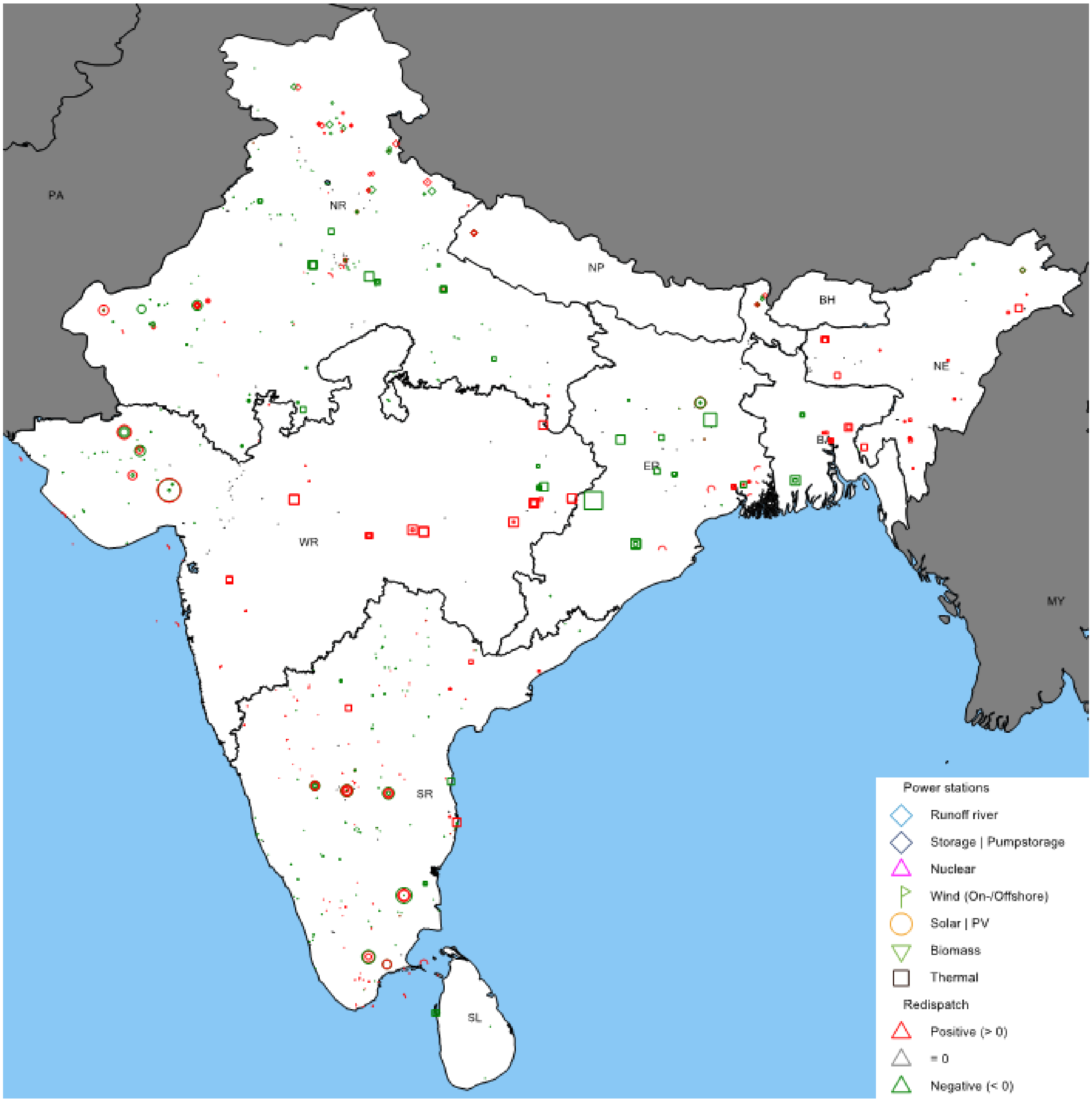


Figure (87) Geographical visualization of the increased power plant generation resulting from redispatch, RES Scenario, in the transmission grid.

The severe reinforcement of grid infrastructure is hence absolutely necessary, especially in the NR-WR, ER-NE and ER-WR cross-border transmission lines respectively. The increase of VRE capacities in the SR region seems to be a better option than the installed capacities in the WR region, especially with the transmission bottleneck situation.

The amount of emissions in the scenario resulting from generation by specific technology types can be seen visualized in the Figure (88). A much steeper decrease in the overall amount of emissions can be easily observed in the simulated results, mostly due to subsequent addition of RES capacities and the effective shutdown of old oil-fired and coal-fired capacities. This can be clearly seen from the Figure (88) that after large solar PV and Wind capacity additions in the year 2015, a sharp decrease of emissions is observed. With the implementation of automatic refurbishments of RES capacities in the simulations, the overall emission values change (mainly decrease) slightly from the year 2030 onwards. The CO_2 emissions by gas-fired plants in the overall emissions output increases at almost a constant rate throughout the timeline, even with an improvement in technology efficiency implemented in the model-i.e., new gas fired power plants have lower emissions than the older ones.

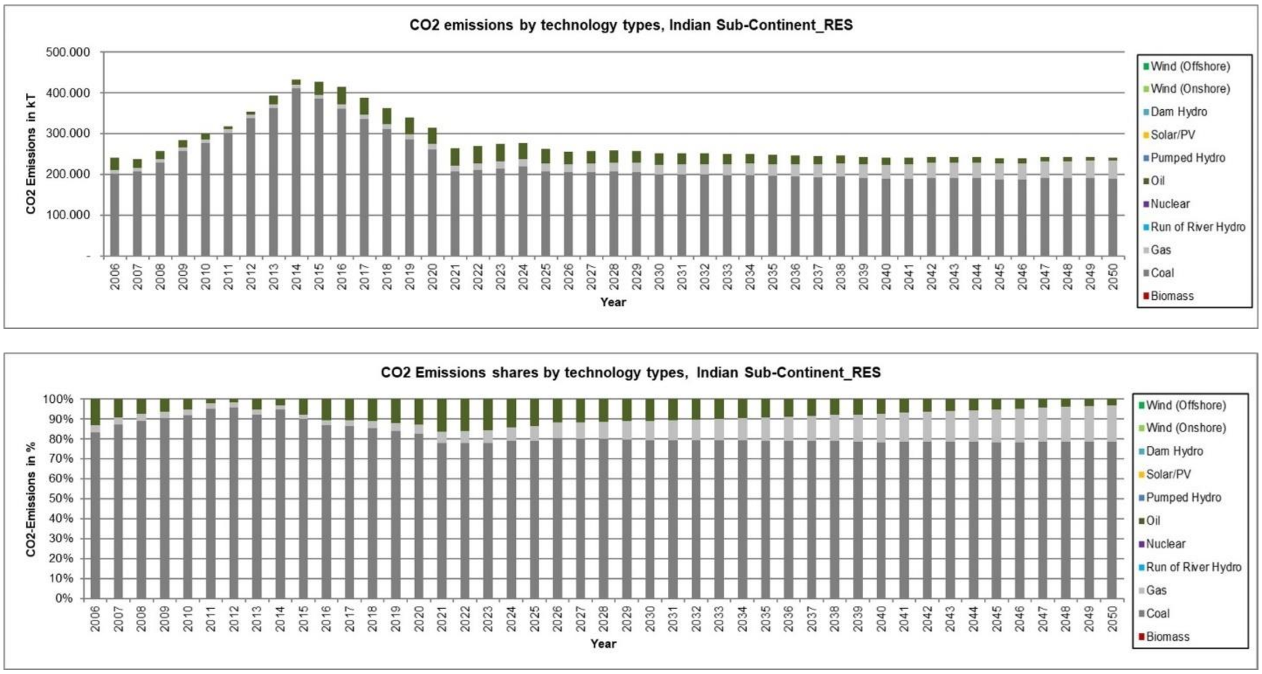


Figure (88) CO_2 Emissions observed from different conventional power plant capacities, RES scenario in kT and by percentage shares

However, with several CCGT capacities replacing coal-fired plants, the emissions from CCGT capacities replaces the decreased share of coal-fired capacities. The total CO_2 emissions resulting from conventional power plant capacities in the power plant mix in the scenario is observed to be a little higher than 247 Million Tonnes of CO_2, which is significantly lower than estimates by several studies [62]. Thus, the overall effect of the RES capacities added show up in the form of an over optimistic emissions reduction, which is more than sufficient to keep up with the country's emissions curtailment goals.

Finally, the electricity prices in the model regions, the average market prices and their development over the simulation timeline is as shown in the Figure (89) below.

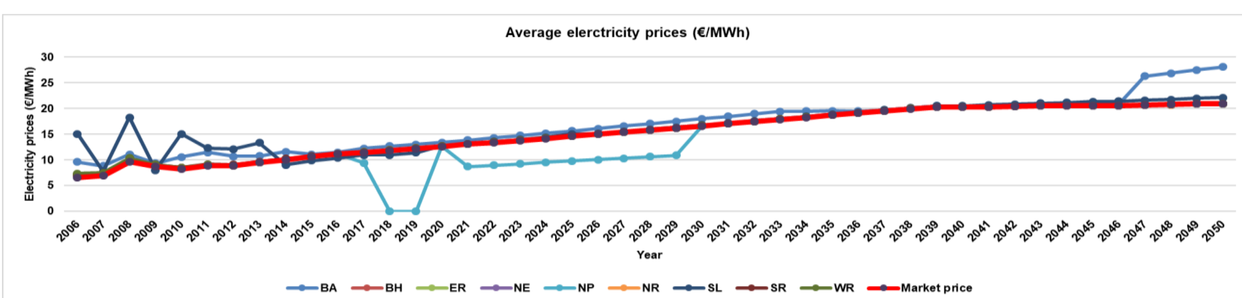


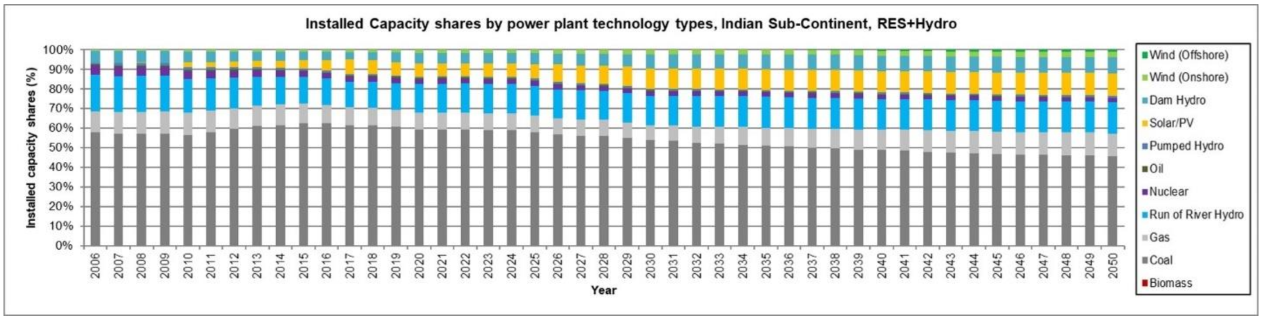
Figure (89) Development of average electricity prices in all regions along with the market price in RES scenario

No large deviations from the average market price is observed other than in the price zones of NP and SL. In NP, the steep drop in electricity prices in the year 2018-2019 is due to the shutdown of the few existing diesel-based oil power plants. The initially large electricity prices in the region SL is due to it being an isolated system until the year 2019 when an interconnection with the Indian region SR is implemented in the form of a HVDC line. The effectiveness of the HVDC interconnection between India and SL is clearly observed in the prices, as the prices in the SL region drop considerably once the HVDC connection is implemented. From the year 2045, an increase in price is observed in the BA region due to the increased import possibility from the Indian region ER, with the effective improvement of interregional transmission.

6.3. Scenario 3 results: RES+Hydro

This particular scenario focuses on the improvement of large hydro power situation in the Indian subcontinent, by introducing large capacity expansions of run-of-river and dam hydro power plants, mainly in the regions of BH and NP. These installations bring about an improved power plant portfolio for the region, possibly restricting a large quantity of CO_2 emissions, and also in supporting the large penetration of VRE technologies like solar PV and wind power capacities.

As in the case of other scenarios, the overall comparison of the power plant capacities installed in the simulated model region, along with the total energy produced by each technology type gives us a brief representation of the technological effectiveness of such a strategy. Several regional impacts and highlights have been clearly discussed later in the 'Discussion' section. The Figure (90) shows the installed power plant capacity in Mega Watts and in percentage shares as defined in this scenario.



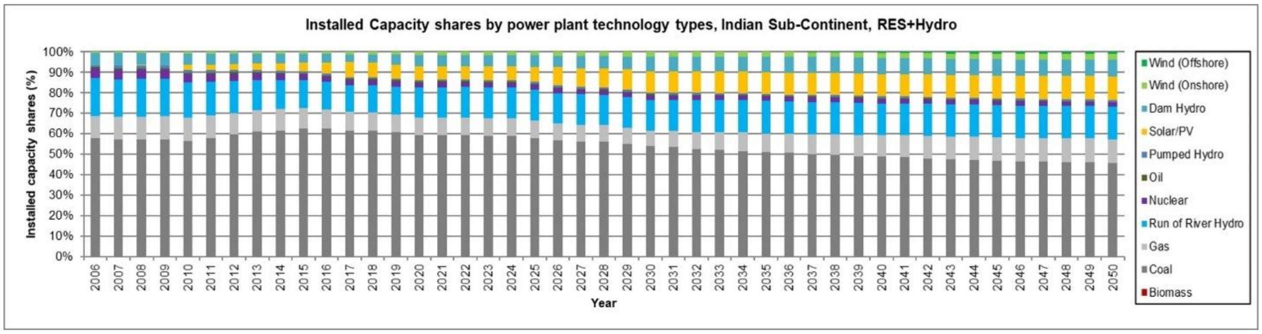


Figure (90) Installed power plant capacities in the Indian subcontinent region for the RES+Hydro scenario, in Mega Watts and in % shares

Comparisons of the installed capacity mix with the total amount of energy produced by each technology type gives us an understanding of how effective each technology type performs in such a scenario. The following Figure (91) gives a representation of the total energy generated by each power plant technology type in the complete model region of ATLANTIS_India. A glance at the shares shows that a large portion of the energy generated comes from run-of-river power plants, and an obvious increase in the energy generated by dam hydro power plants is also observed. Energy generated by solar PV, onshore and offshore wind remains comparatively almost the same as in the RES scenario, even with a smaller capacity indicating that these technologies work really well with dispatch-able renewable hydro power technologies.

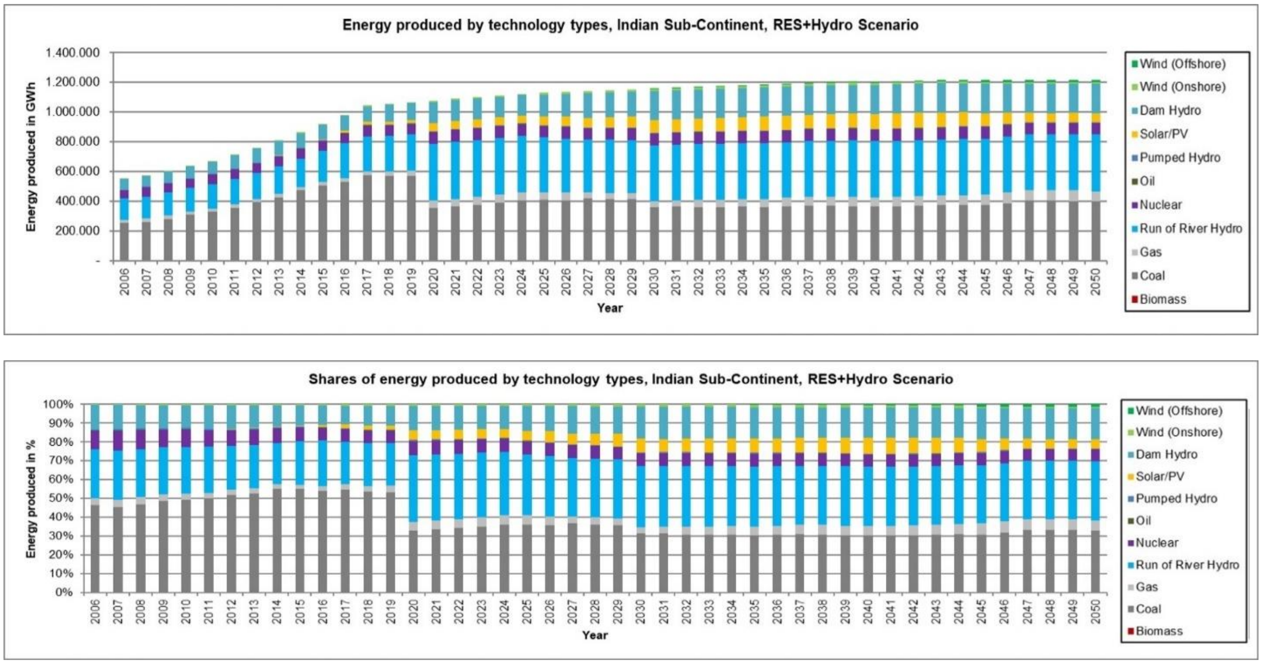


Figure (91) Energy produced by power plant technology types, RES+ Hydro scenario, Indian subcontinent, in GWh and % shares.

A decrease of almost 13 percent is observed in the energy produced from coal-based power plants in the year 2050 from the 2014 values. CCGT replacements fill up the void created by coal-fired power plants which are shut down (without lifetime extensions planned), at the end of their technical lifetimes. Also, it is observed that a small increase in the dam hydro power plant capacity brings in a substantial increase in the share of energy produced by hydro based technologies in the energy mix of the simulated scenario.

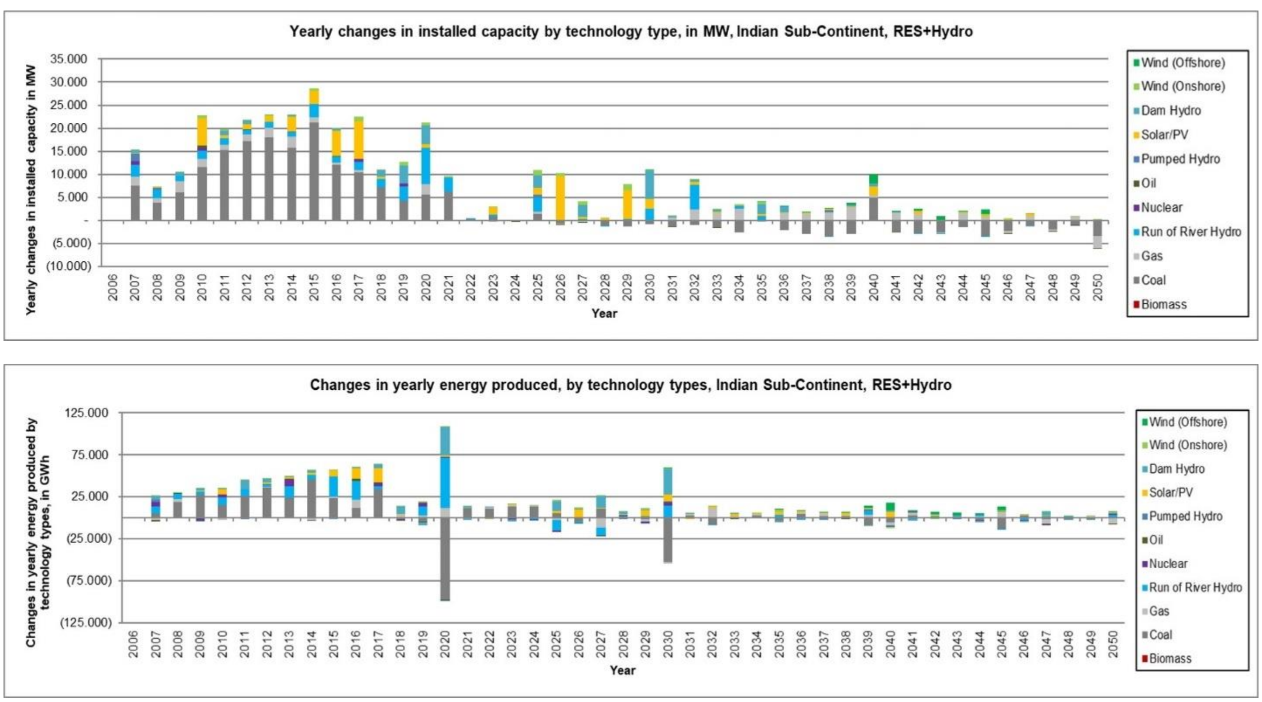


Figure (92) Yearly changes in the share of energy produced by each technology type in the RES+Hydro scenario.

A more detailed variation in the energy produced can be observed in the Figure (92), which shows the simulated yearly change in energy produced by each technology type. A large increase in energy generated by run-of-river and dam hydro power plants is observed in the year 2020, when most of the large hydro power installations in the regions of BH, NE and NP are commissioned. A subsequent decrease in the energy generated by coal-based power plant capacity is also observed in the same year. In the year 2030, around 20 GW of large dam hydro capacity expansions by the GoI in the BH and NP regions would be commissioned, and a clear impact can be observed in the year, i.e., a large reduction in the energy generation from coal-fired and gas-fired capacities, even with some planned capacity additions. It should also be noticed that the energy production by solar PV and wind are also gradually increasing, especially with the addition of hydro power capacities in the year 2020. This shows the effectiveness of DRE technologies like hydro power strategically planned along with VRE technologies like solar PV and Wind in the energy system of the Indian sub-continent.

The resulting load flows in the transmission system also become important, as most of the hydro power expansions, are done in the regions of BH, NE and NP with weaker transmission infrastructures and connectivity. Several interconnections connecting these regions to stronger networks in the Indian power sector have been proposed after the year 2025, along with the reinforcement of 132 kV network in the NE and NP regions. The Figure (93) shows the resulting load flows resulting from RDZP market simulations for the year 2050, August, Peak 'a' period in the transmission network of the Indian subcontinent.

The transmission network in the northern part of the subcontinent seems to be heavily loaded, as all the large hydro power capacity expansions are planned majorly in the regions of BH, NE and NP. However, a big change in the bottleneck situation in the NR-WR region is observed, in comparison with the BAU and RES scenarios. The previously observed congestion in the NR transmission lines have been reduced considerably, though congestion around RES capacities in NR still remains. More bottlenecks are now observed in the NE region, even with heavy reinforcement of the 132 kV lines implemented in the region. This would mean that the GoI has to improve their efforts in the improvement of grid infrastructure in the NE and NR regions before the implementation of any RES or hydro based strategies.

Furthermore, the completed 'electrical highway' in the NP region again seems to be really important in managing power transmission issues and the integration of the planned hydro power expansions. The new 220 kV grid could probably need extra reinforcement to effectively add more hydro power in the NP region. The load flow situation around the new 220 kV transmission infrastructure in the NP region, proposed to support a large exchange of power from hydro power plant capacities planned in the NP region by the GoI is as shown in the Figure (94). The transmission line seems to be heavily loaded, meaning a large amount of electrical energy generated by the hydro power plants in the NP region are exported to the Indian regions of ER and NR. Also, this 'electrical highway' helps complete a transmission ring with the regions BH and ER, which helps in the effective transmission of power in the region. The effective power transfer between the three regions mentioned is of utmost priority in this scenario.

Bottlenecks are also seen in the interconnections between the region BH and the regions ER and NE, indicating the large amount of export/import of electricity between the regions. These heavily loaded cross-border capacities across the NE-BH regions could result in redispatch of power flow across the transmission bottleneck, and could also reduce the overall generation ability of the planned BH power plant fleet.

In a nutshell, the overall congestion observed in the RES scenario seems to have reduced, leading to a conclusion that the addition of hydro power capacities is an effective strategy to be implemented along with the increase of VRE capacities.

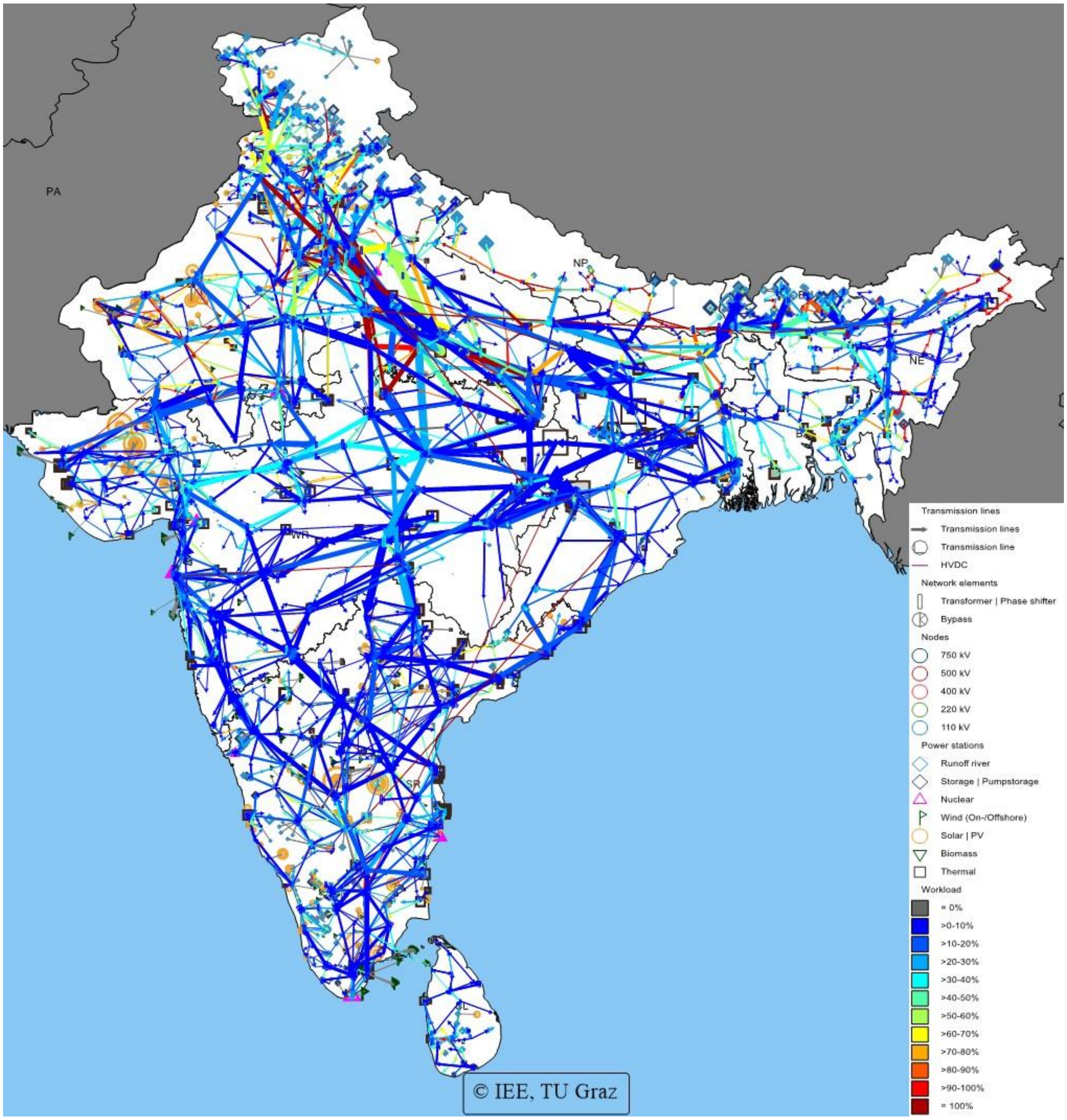


Figure (93) Load flows resulting from redispatch in the simulation year 2050, August Peak 'a' period

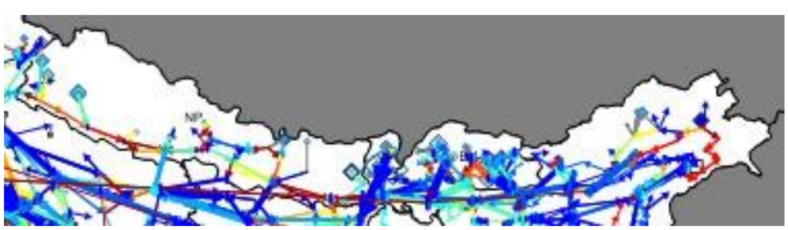


Figure (94) Load flows resulting from large addition of hydro power capacities, RES+Hydro Scenario- in the BH, NP and NE region, highlighting the effectiveness of the 'electrical Highway' in the NP region.

A look at the positive or negative redispatch in generated energy from specific technology types in the installed capacity mix gives us an idea of how the power plant capacities behave to compensate for the bottle neck situation in the scenario. The Figure (95) shows a brief representation of positive or negative redispatches in the different power plant technology types in this scenario.

The generation from hydro power plants seemed to be heavily affected by redispatch of power flow due to transmission grid restrictions, in comparison with the RES scenario discussed previously. Majority of the coal power plants in the region around the demand centre compensate for the limitations for power flow created by the transmission bottlenecks around several of the proposed run of river hydro capacities. A small portion of dam hydro also contributes towards easing the bottleneck situation, as seen from the Figure (95).

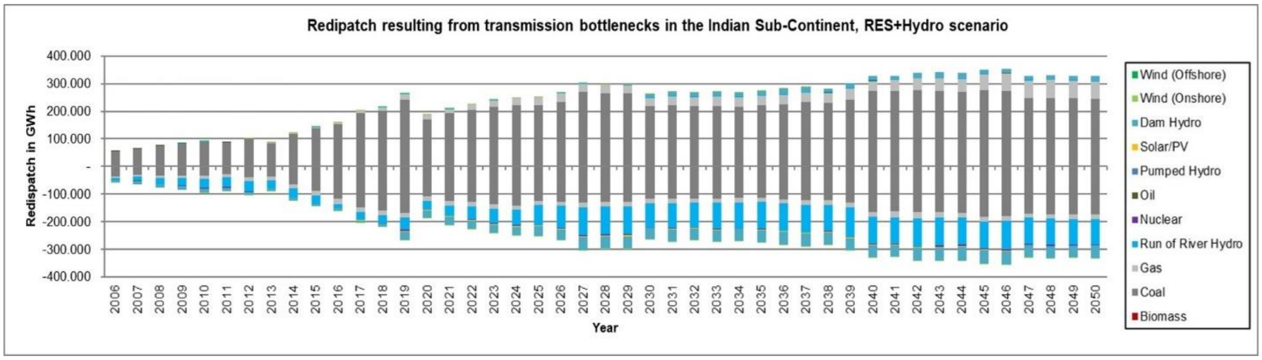


Figure (95) Positive or negative redispatch observed in installed capacity technology types in the RES+Hydro scenario

A Figure (96) provides the geographical visualization of positive and negative redispatch power plants in the August Peak ‘a’ period, 2050 in comparison to the august peak ‘a’ period in the year 2049, as an example.

The geographical visualization of the positive and negative redispatch differences occurring in power plants would give us a clear understanding of the transmission bottleneck versus generation situation in the scenario. It can be observed that several coal-fired generation capacities have a large positive redispatch differences, in comparison with several of the run of river hydro capacities.

The hydro power capacities in the BH region have positive redispatch difference, and the thermal capacities in the NE region show considerably smaller differences in comparison to RES and BAU scenarios. The hydro power capacities in the northern part of the ER region show negative redispatch differences, meaning a large portion of generating capacity in the region is withheld due to transmission capacity constraints. A few of the many thermal capacities in the SR and WR regions also seem to have negative redispatch differences, especially due to the regions being import dependent and the transmission limitations observed. So, for a better integration of hydro power capacity in the north, the transmission system in the northern region needs to be heavily reinforced.

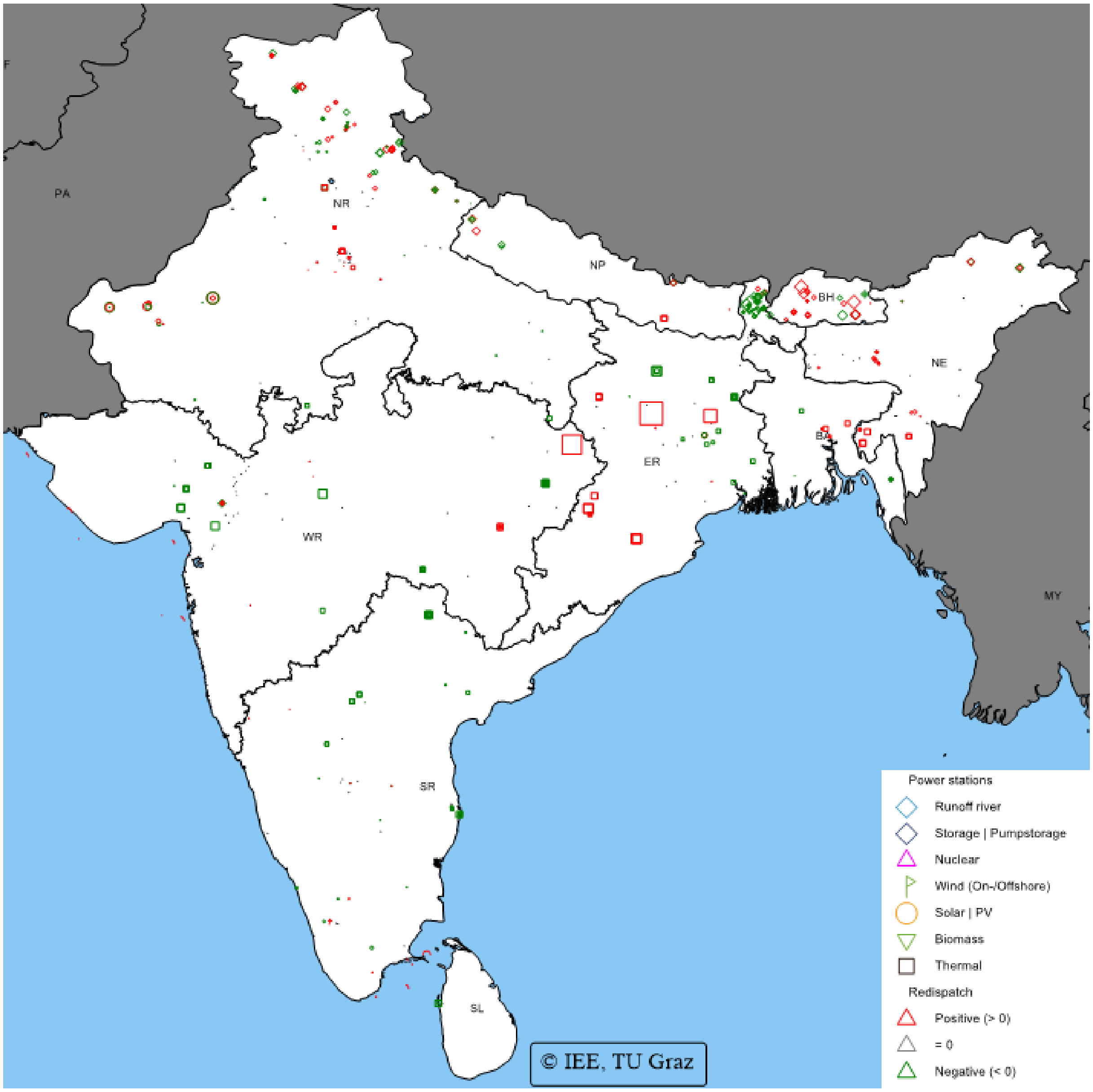
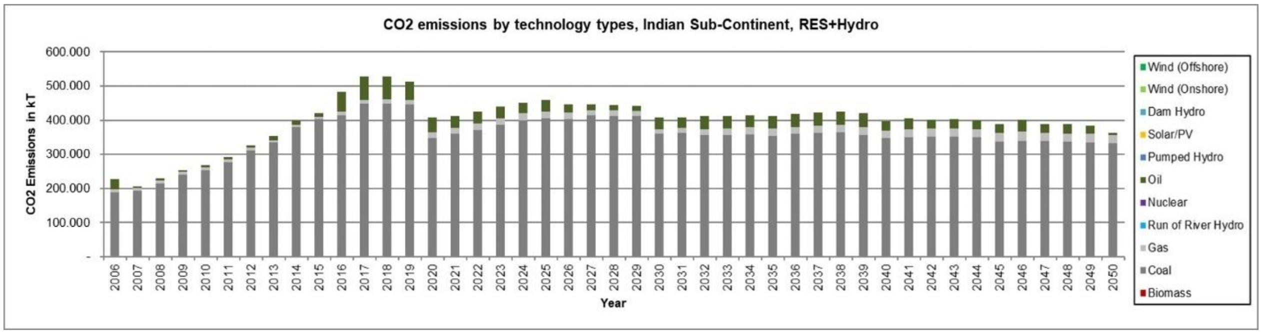


Figure (96) Geographical visualization of the increased power plant generation resulting from redispatch, RES+Hydro Scenario –August Peak 'a' period in 2050 with August Peak 'a' period in 2049

The resulting CO_2 emission values also become interesting as such a strategy could effectively solve the region's challenges regarding energy related emissions. The Figure (97) provides us an overall view of the resulting CO_2 emissions by different technology types up to the simulation target year 2050.

A decrease in the emissions is observed majorly after the addition of large hydro capacities in the year 2020, a gradual increase till the year due to the addition of new coal and CCGT replacements until the year 2030, when another set of large hydro capacities would be commissioned.



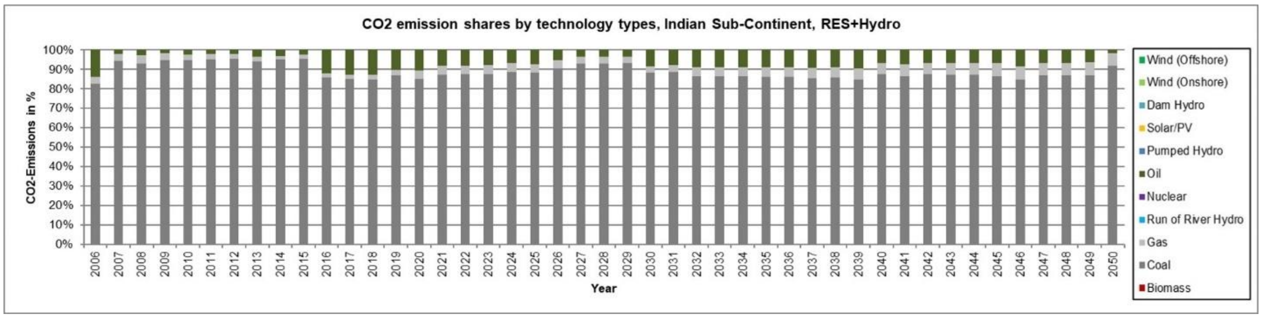


Figure (97) CO_2 emissions observed from different conventional power plant capacities, RES+Hydro Scenario- in kilo Tonnes (kT) and by percentage shares

After the year 2030, a gradual decrease in the CO_2 emissions is observed, due to subsequent additions of run-of-river and dam hydro power capacities with each year. The share of emissions by gas-fired capacities remain almost constant, mainly due to several oil-fired power plants going offline. The overall emissions of the RES+Hydro scenario is subsequently higher amounting to around 360 Million Tonnes of CO_2 in the year 2050, compared to 210 Million Tonnes of CO_2 in the RES scenario.

The average price of electricity in each region is also compared to give an idea of the economic effect of the implementation of this particular scenario. With the addition of large capacities of hydro power and other RES technologies, the average price resulting in the Energy only Market is expected to be significantly lower than the previous scenarios.

The Figure (98) shows the comparison pf the development of average electricity prices in all the model regions, along with the average market price observed until the year 2050.

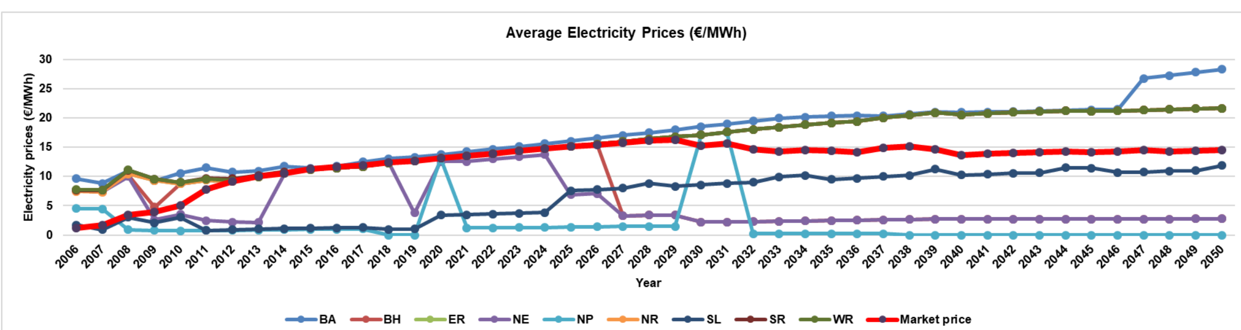


Figure (98) Development of average electricity prices in all model regions along with the average market price, RES+Hydro Scenario

The Indian regions of ER, NR, SR, and WR, and the region of BA all show higher than average electricity prices. The prices in BH and NE follow almost show the same variation, with the largest share of hydro power expansion happening in these regions. The prices in the NP region stays almost close to zero, showing fluctuations only when additional diesel-based capacities go online/offline. An increase of the price in the BA region in the year 2045 is observed, and is a resultant of increased import from the Indian region ER, similar to the electricity price evolution in the RES scenario.

6.4. Scenario 4 results: Nuclear

As discussed in the scenario definition, this scenario is significantly different than the other scenarios, where the focus is on nuclear power technologies, especially the new thorium-based HT-FBR developed by India with cooperation from Russia. Even if the HT-FBR technology produces comparatively smaller quantities of nuclear waste and almost close to weaponizable fissile material, the use of nuclear technologies is highly dangerous in many ways, and is discouraged in the course of this thesis.

As in the case of other scenarios, the initial evaluation of the simulation results is also done by comparing the installed capacities with the amount of energy generated by the specific technology types. Many studies [12][29] have suggested vigorous expansion of nuclear based generating technologies could be an effective solution for the challenges to sustainable energy in the Indian subcontinent. The Figure (99) illustrates the aggressive expansion of nuclear capacities in the Indian subcontinental region, including 4 GW of BWR capacities in the regions of BA and SL, which are installed with supports from the GoI and Russia. A brief look at the installed capacities show a rather aggressive five-fold nuclear expansion in the power plant fleet of the Indian subcontinent, beginning in the year 2025- from 6 GW in 2019 to around 28 GW in the year 2050.

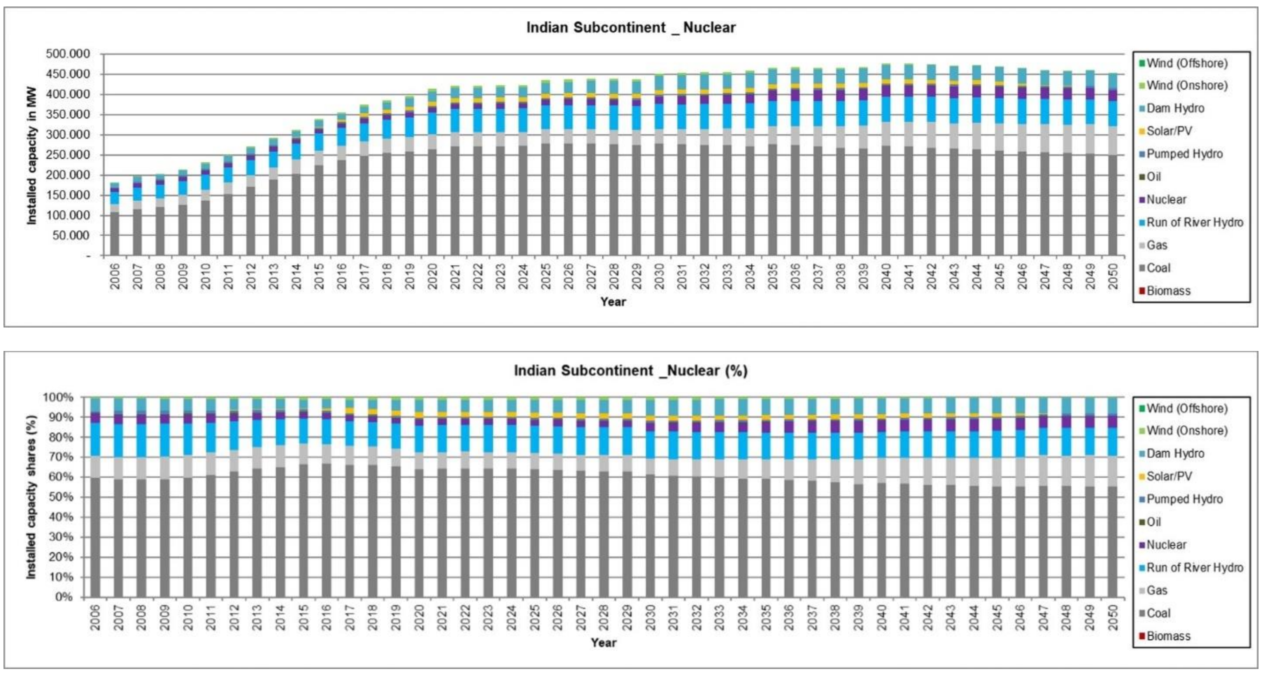


Figure (99) Installed capacity by power plant type in the Nuclear scenario in GW and the share of nuclear capacities in defined in the scenario

The comparison of the energy generated by the nuclear capacities in the power plant mix show the overall effectiveness of such a strategy. The Figure (100) gives us a representation of the overall energy generated in the region by the several technology types, highlighting the share of nuclear technologies in the capacity mix. A definite decrease in the share of electricity generated by coal-fired capacities is observed, pushing the share well below 40 percent in the final energy mix. The proposed CCGT replacements are effective, as in the case of other scenarios. This is in terms of improved flexibility and support for peak load operation. The share of hydro power and dam hydro power almost remains the same, and pumped hydro plants are almost not used at all. The observed share of electrical energy generated by solar PV and wind capacities are really small. The share of these capacities disappears both from the capacity mix and the energy mix in the final years of the simulation, as refurbishment of these technologies is not considered, just like in the BAU scenario.

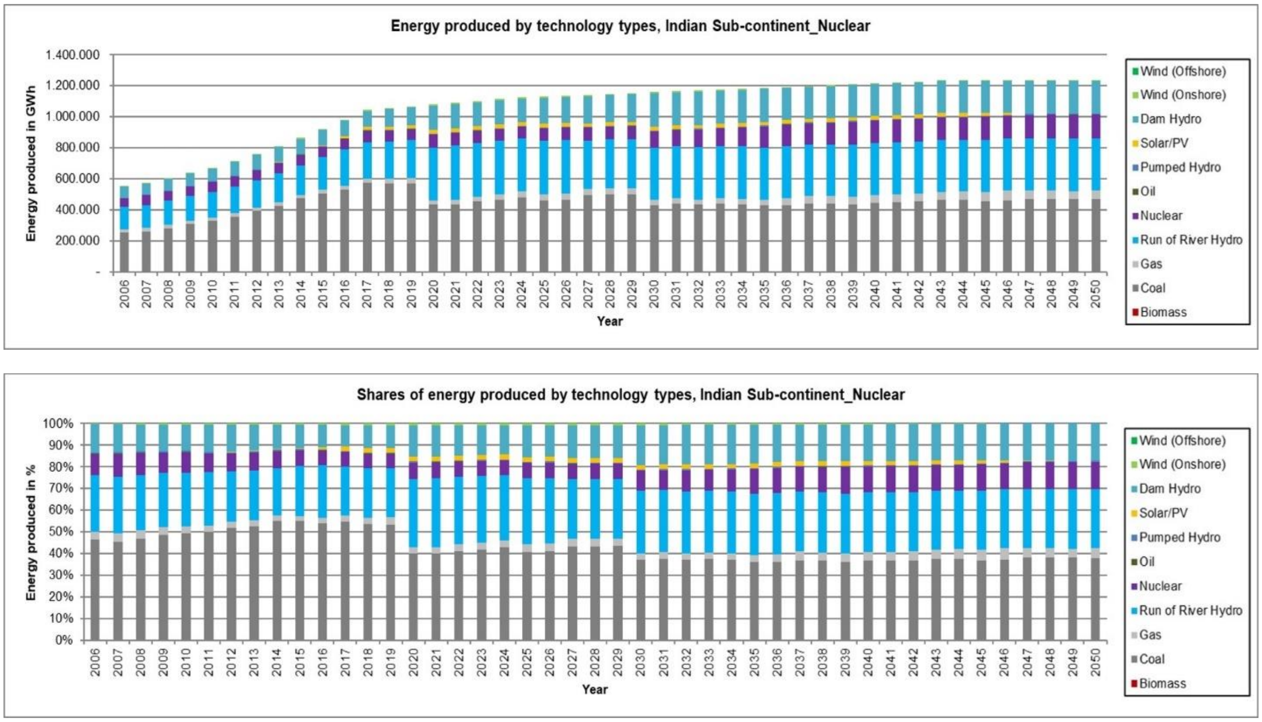


Figure (100) Electrical energy generated by various technology types, in the Nuclear scenario, in GW and in shares of the energy mix in the subsequent simulation years.

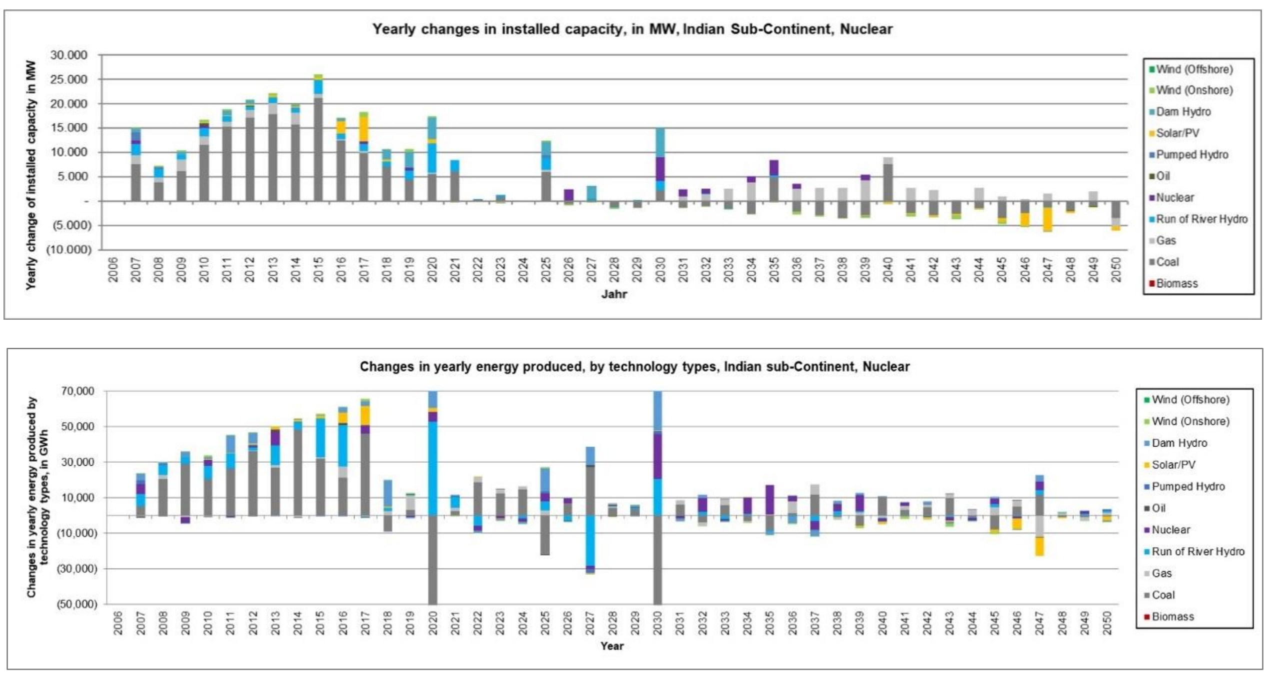


Figure (101) yearly changes in electrical energy generated by specific technology types, nuclear scenario

The changes in energy generated with each year, based on technology types show the effectiveness of each capacity additions in the power plant fleet of the Indian subcontinent. The Figure (101) shows the yearly changes in the installed capacity and electrical energy resulting from capacity additions, highlighting the contribution of newly commissioned nuclear capacities.

It can be observed that with every capacity of nuclear power plant added, there is a subsequent increase in the share of electrical energy generated by nuclear power plants, and a large decrease in the energy from coal-fired technologies. Hydro power, a DRE technology, can be expected to have stable generation output. The hydro power capacities also add a large share of electrical energy each year when additional capacity is commissioned.

The load flows resulting in the transmission network due to power flow and redispatch in this scenario is as shown in the Figure (102) below.

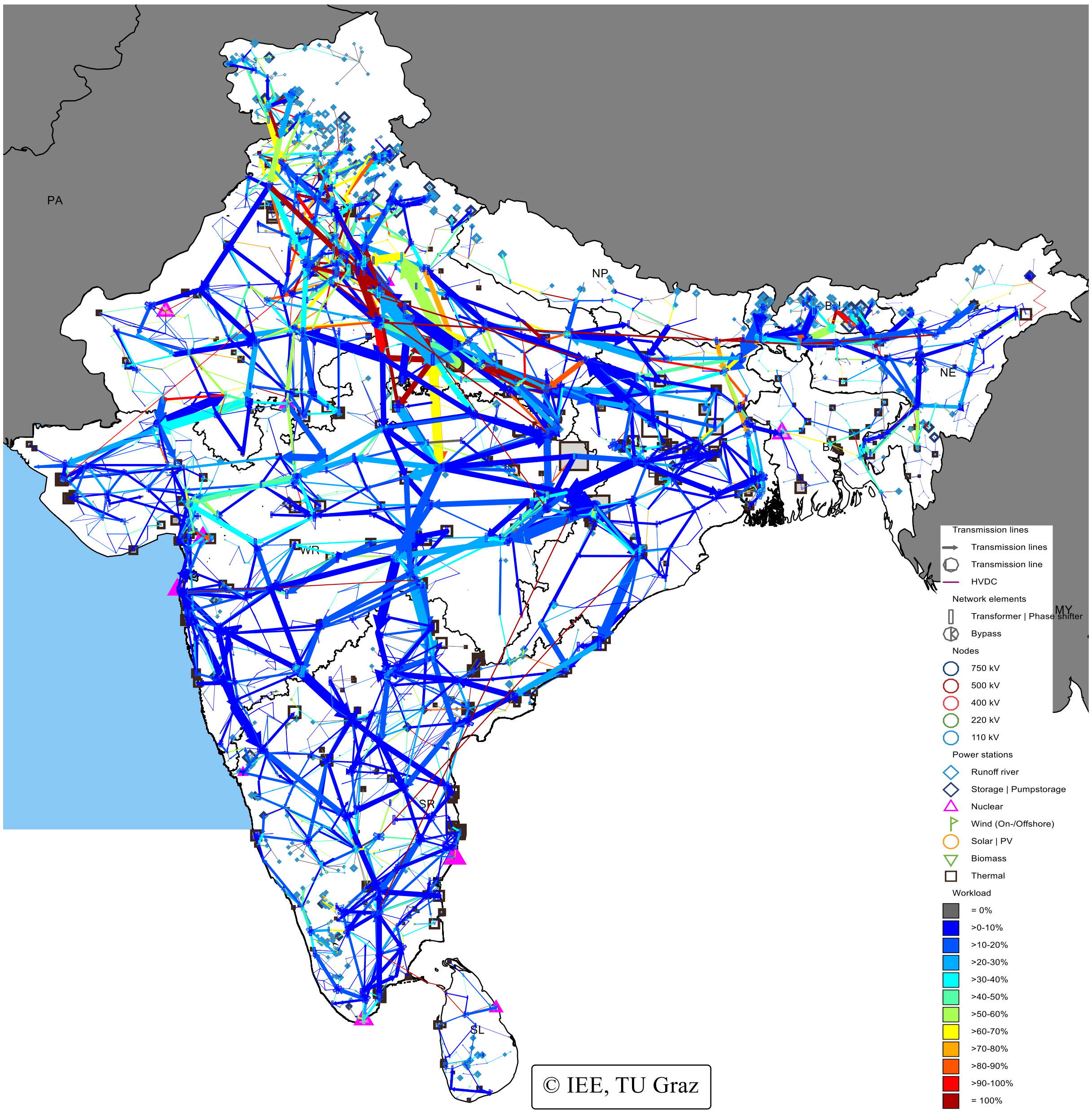


Figure (102) Load flows in the transmission network resulting due to redispatch, Nuclear Scenario, in the year 2050 as visualized from simulations in ATLANTIS_India.

The resulting load flows show critical bottle necks in the NR region, and in the NE and NP regions similar to the other scenarios, suggesting an overall reinforcement of the grid in the said regions. The interconnections between the regions BA, SL and the Indian power regions also look heavily loaded. In the case of interconnection between SL and SR, this can be taken into consideration that the HVDC interconnection link is especially useful in transporting the excess energy from additional nuclear capacity in the region SL to the region SR. However, in the case of BA, the 400 kV AC interconnections, which are overly loaded would suggest that severe reinforcement of the grid is absolutely necessary for the implementation of nuclear capacity in the region. The interconnection between BH and NE regions also seem to be heavily loaded, and this bottleneck could be a problem for capital intensive hydro power investments in the BH region. With new nuclear capacities popping up in the western region of NR and the region WR, the interconnections between these regions must be analysed in detail.

With subsequent 765 kV transmission capacities already implemented in the SR regions, the new Th-FBR power plants can effectively transmit the electrical energy generated to the subsequent load centers in the SR region. However, the cross-border lines between SR and WR also demand reinforcement, as they are already critical points of bottlenecks in the transmission network.

Another significant change observed in the power plant utilization is that several of the larger coal-fired power plants in the ER, SR and WR regions, which are relatively more expensive than the newer ones can be seen to be completely ignored (no shading), with the cheaper option of generation from the extra added nuclear capacity. Thus, it can be said that the nuclear power plants in the subcontinent can be an effective replacement to a majority of the carbon-intensive older coal fired power plants in the region.

It can be observed from the Figure (103) depicting the differences in generation by power plant types that the coal-fired, gas-fired capacities along with a few dam hydro capacities compensate with increased generation due to the bottleneck situation observed from the load flow visualizations. The nuclear power plants are expected to decrease their generation with a negative redispatch difference, along with VRE capacities, and a significant share of run of river hydro capacities. Transmission bottlenecks around the vicinity of nuclear capacities may be the cause of negative redispatch differences observed in the nuclear capacities, which would have to be compensated by increased share of generation from coal fired capacities in the vicinity of the demand centres. Improvement of transmission infrastructure around the added nuclear capacities and specific DSM measures in these demand centres could prove effective make the nuclear capacity additions much more effective altogether.

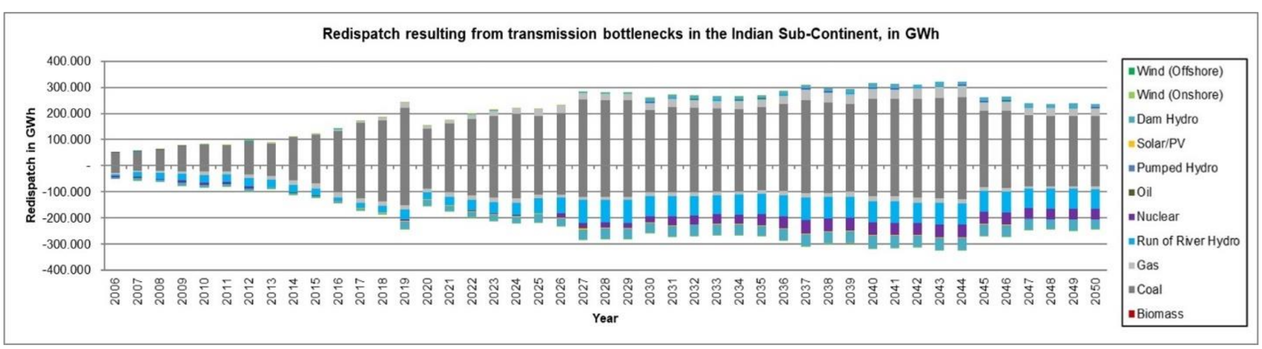


Figure (103) positive and negative redispatch observed in the generation, Nuclear scenario from different capacities resulting due to bottlenecks in the transmissions system, 2050.

The Figure (104) visualizes the geographical representations of the power plants in which positive or a negative difference resulting from the RDZP market simulations are observed, in 2050 August peak ‚a' period, in comparison with 2049 August peak ‚a' period. It can be observed that the extra added nuclear capacities in the region of BA and SL and a few units in the Indian regions show a negative redispatch differences, which would mean that if not for transmission congestion in the region, the power plants could have contributed more to the generated energy mix. Similarly, the run of river hydro plants in the BH and ER region show similar negative redispatch differences.

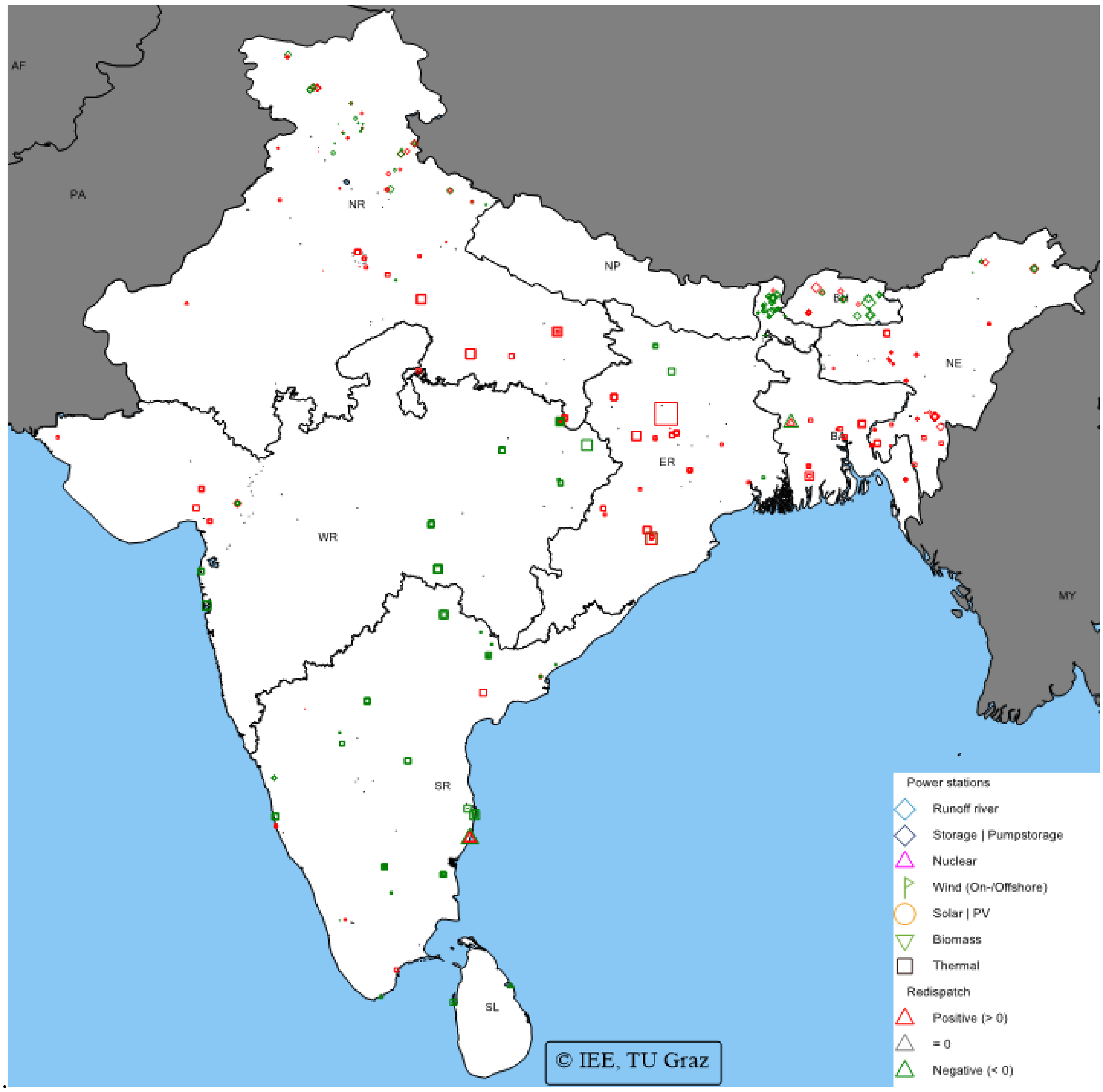


Figure (104) Geographical visualization of positive or negative redispatch differences, Nuclear scenario- occurring due to transmission bottlenecks in the Indian subcontinent region

The energy related CO_2 emissions calculated by the model, with the addition of nuclear capacities can be seen in the Figure (105). Though as not as effective as the RES and RES+Hydro Scenarios, the addition of nuclear capacity does have an effect when compared with the BAU scenario. The overall CO_2 emissions resulting from the generation in the power plant fleet of the nuclear scenario comes close to around 380 million Tonnes of CO_2, which is significantly higher than the RES scenario and lower than the BAU and RES+Hydro scenarios as discussed. Significant reductions in CO_2 emissions can be observed in the nuclear strategy, in comparison with the BAU scenario. The proposed CCGT replacement capacities providing peak load flexibility options add to the overall emissions, along with coal-fired generation.

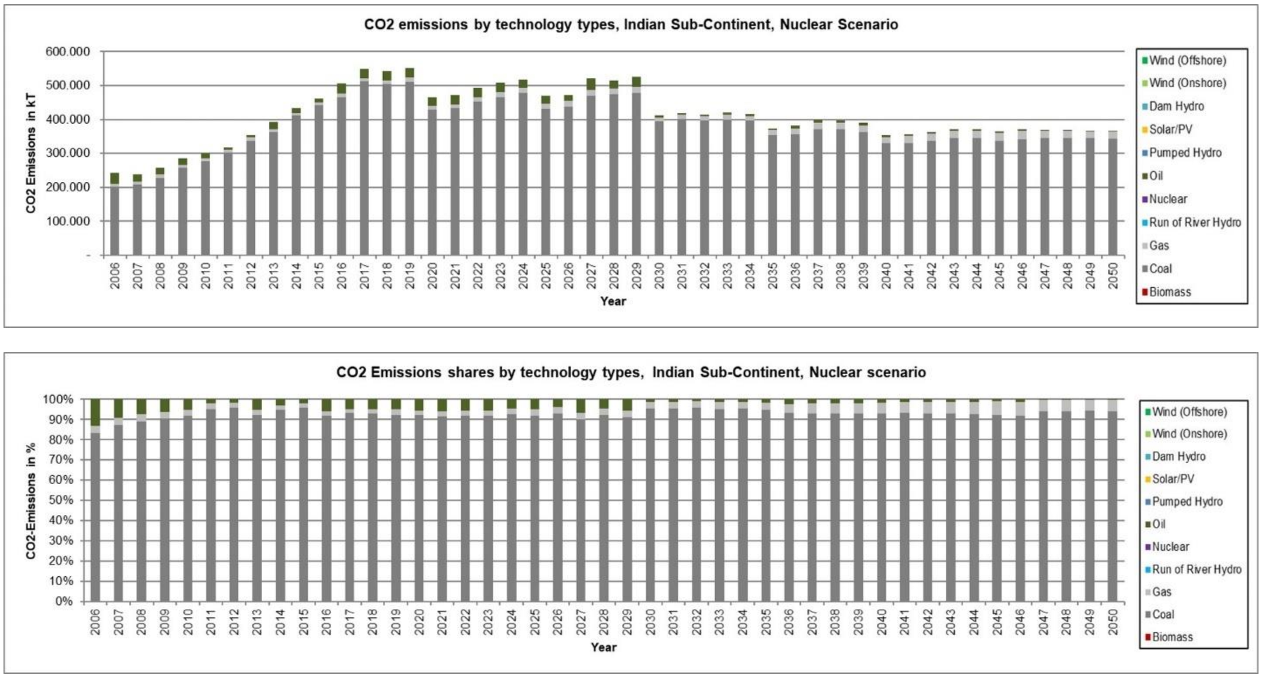


Figure (105) CO_2 emissions resulting from the electrical energy generation by the power plant fleet in the Nuclear scenario.

A brief representation of the regional market price evolution gives us the understanding on how the added nuclear capacities influence the electricity prices in the subsequent region. An illustration of the price evolution can be seen in the Figure (106) below. The Indian regions, except the regions of ER and NE, all follow similar trend as the average market price. The NP region shows a similar trend, as in the case of the other scenarios.

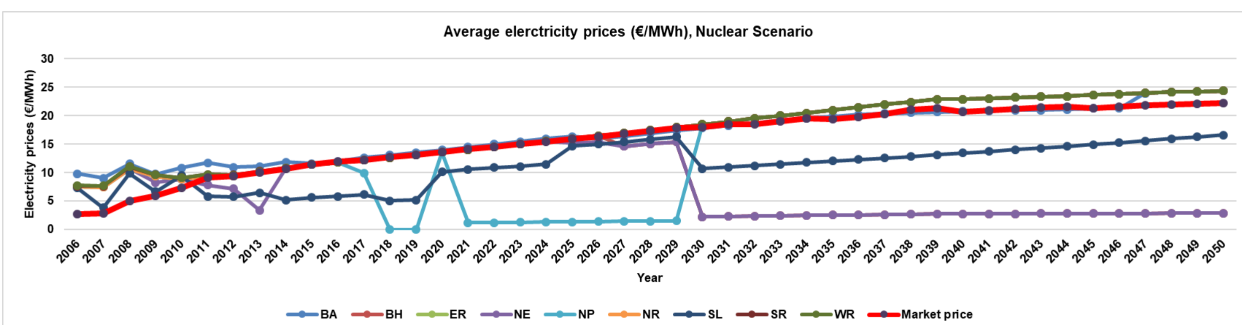


Figure (106) Market price evolution in various model regions, in the Nuclear scenario until the target year 2050

The price in the region SL increases with the implementation of the HVDC link, also decreases with the addition of its own nuclear capacity. The NE region shows a large decrease of electricity price in the year 2030, with the improved interconnection with the BA region and addition of hydro power capacities. The region of SR and WR have the highest prices in the scenario.

6.5. Capital Stock calculations: RES +Hydro

As explained, capital stock calculations matter with technologies having high capital intensities over large technical lifetimes, For the scenario including both integration of solar PV, onshore and offshore wind and specific hydro power expansions in the regions of BH and NP (RES+Hydro), the GCS and NCS were subsequently calculated for each region defined in the model ATLANTIS_India.

An overall comparison of the evolution in the GCS and NCS in all the model regions was initially conducted, to get a bird's eye view of the capital stock situation in the subcontinent power plant fleet. This is represented in the Figure (107) as shown.

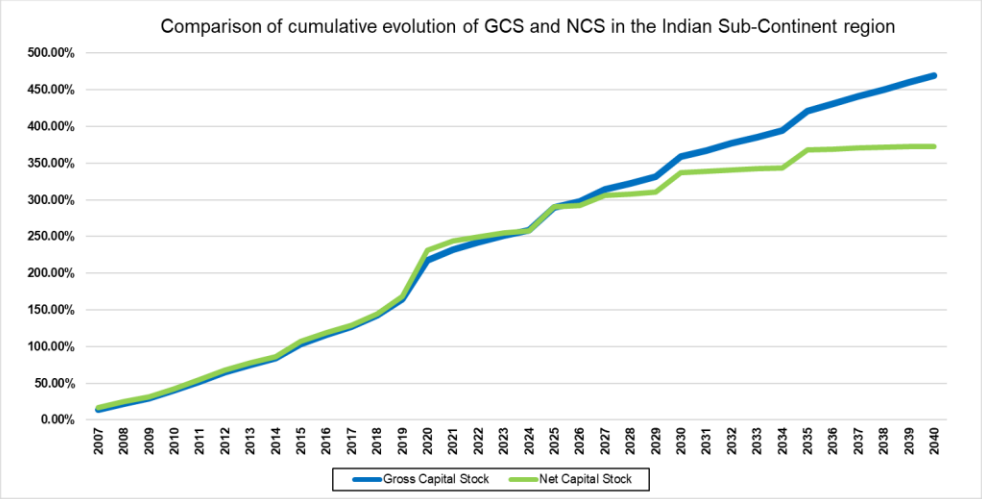
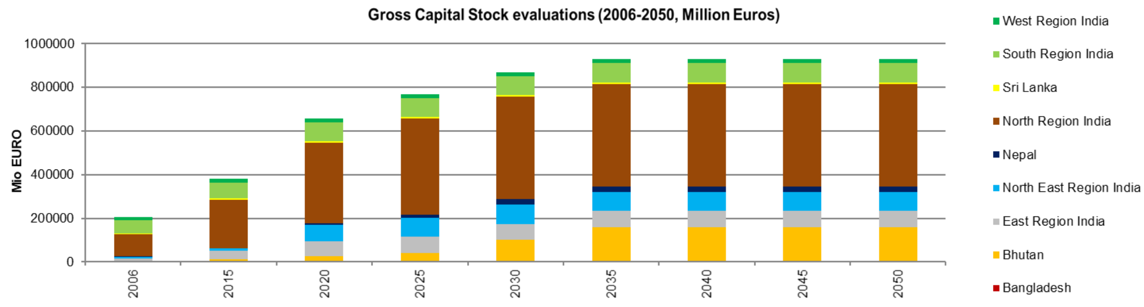


Figure (107) Comparison of the increase in the overall Gross and Net capital stocks of all the regions defined in the ATLANTIS_India

It can be observed that there is a large increase in the overall capital stock of the power plant fleet. As most of the power plants in the power plant fleet are relatively new, the difference in the GCS and NCS is observed in the later stages of the timeline, especially with the depreciation of the thermal power plant assets.

Also, an overall comparison of the increase in GCS and NCS calculated for each model region defined is as shown in the Figure (108). A seemingly large increase in the capital stocks of the region of NR is observed, with the subsequent expansion of hydro power capacities. The proposed large expansions of solar PV and Onshore wind capacities in the SR and the WR fail to create an overall effect in the increasing of capital stocks in the respective regions. The larger differences in the GCS and the NCS observed in the Indian regions are specifically due to the depreciation of larger coal-fired capital-intensive assets. Addition of 5 GW of nuclear capacity also boosts the capital stocks to a certain extent in the model regions, in comparison with coal-fired and gas-fired generation assets.

With several new hydro power plants planned by the GoI and the Bhutanese government in the year 2030, the capital stock of the BH regional power sector gets a tremendous boost. With larger life times of hydro power capacities, the capital stock of the Bhutanese power sector gains a large share of wealth over a long duration of time.



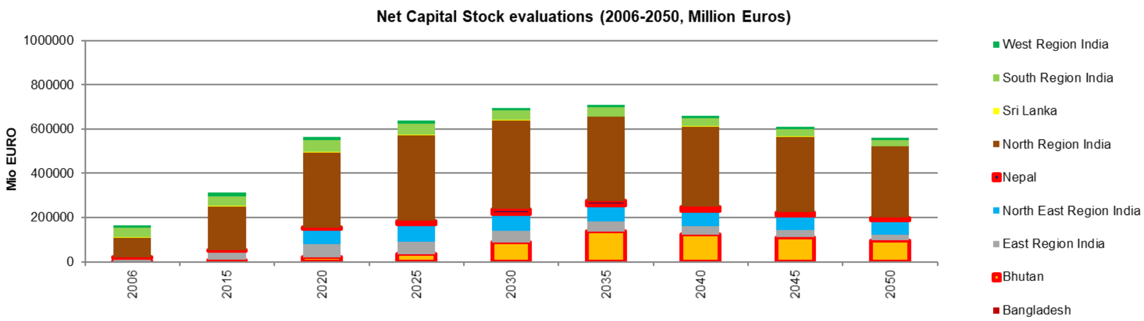


Figure (108) Comparison of the Gross (above) and Net Capital Stocks (below) in each power region of Atlantis_India

The Figure (109) gives a brief representation of the overall shares of the technology types in the NCS build up for the Indian subcontinent region. A large part of the NCS calculated for the region comes from hydro power plants, run of river, dam hydro and pumped storage. This evaluation specifically highlights the importance of the hydro power plant capacity in the energy system of the Indian subcontinent region. The capital stock intensive nature of the nuclear power plant capacities can also be observed in the accompanying figure. The NCS of the coal fired power plants seem to decrease largely in towards the end of the timeline.

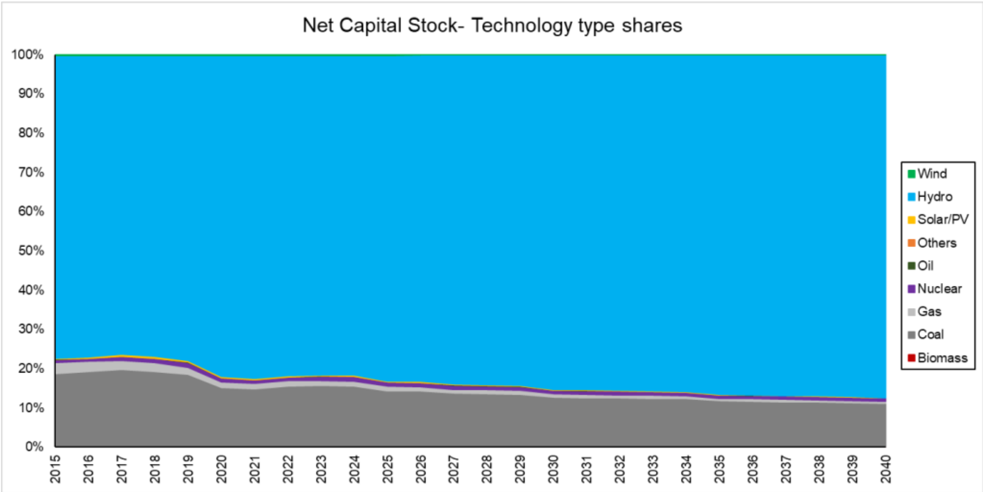


Figure (109) Technology shares in the Net Capital Stock in the Indian Sub-Continent

A comparison of the calculated depreciation values gives us an estimation of the loss of the value of installed capacities, in the year 2040. The Figure (110) gives us the comparison of depreciation values by power plant types in the base year 2006 vs the year 2050. It can be observed that that the depreciation value of the hydro power share remains almost the same, while there is a seemingly large increase in the depreciation values of the thermal power shares, including coal and gas. Coal power plants show the largest depreciation values in the thermal power share.

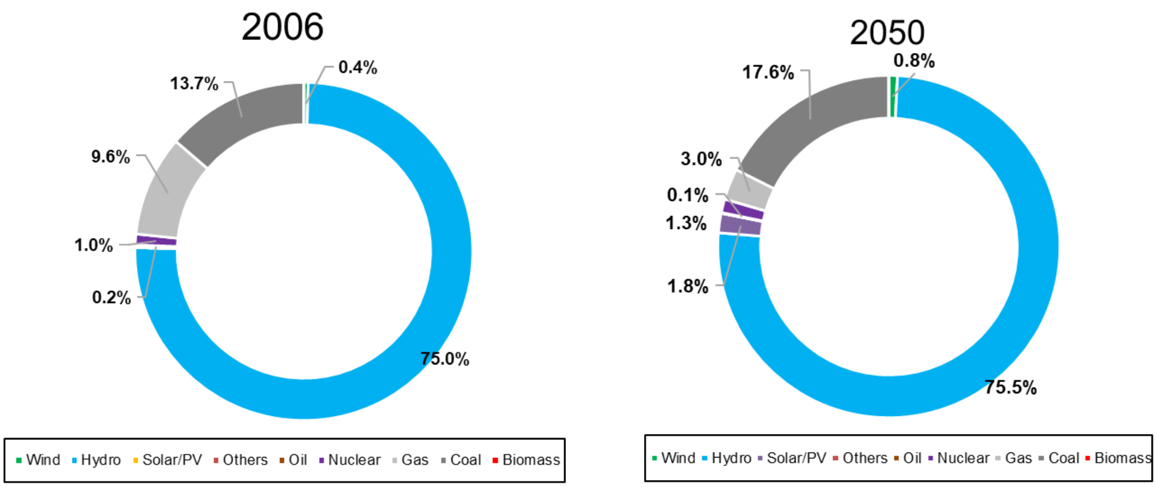


Figure (110) Depreciation values by power plant types in the RES+Hydro scenario *2006 (left), and 2040 (right)*

This leads to an understanding that with regards to the NCS analysis, Hydro power capacities like run of river hydro, dam hydro and pumped hydro power plants are more capital stock intensive than thermal power plants of the same capacity, mainly due to the longer technical lifetimes of hydro power plants, higher capital intensities, and the larger amount of depreciation observed with thermal power plant assets.

7. Discussion: Results

Results specific to regional energy systems in each scenario are further discussed, as specific regions show interesting behaviors in specific scenarios. These discussions provide an understanding of the simulation results on a regional level, and in turn further contribute to a higher understanding at the model level. Specific behaviors interesting in the scope of this thesis include installed capacity shares of different technology types, and the electrical energy generated, regional positive and negative generation differences occurring mainly due to redispatch resulting from transmission bottlenecks, and the resulting import export between these specific regions. With the increased expansion of VRE capacities only in the SR and WR regions, it becomes important to also look at the effectiveness on a regional level, as sometimes the overall simulations fail to highlight the regional differences with other interconnecting systems coming in to play. Furthermore, the capital stock analysis of the RES expansion along with aggressive hydro power expansions in weak energy systems of BH and NP regions, even with the simulation mechanism centered around welfare optimization, the regional wealth of the systems in these regions and the specific economic impacts have to be discussed in detail. The following regional impacts are highlighted in the scope of this discussion chapter.

7.1. BAU Scenario: carbon emissions in the WR region due to clean coal strategy

The implementation of 'clean coal' in the regions of NR, SR and WR has a smaller but positive impact on the resulting CO_2 emissions from the respective regional power plant fleets. Without a large expansion of nuclear and hydro capacities, the BAU scenario demands a cheap and stable source of electricity, from the year 2035, and especially in the end of the 2030s where a majority of the larger and older coal power plants are eventually shut down due to the end of their technical lifetimes. The smaller CCGT replacements have been observed to be generally effective in all the scenarios. However, in the case of BAU scenario, the requirement for larger capacities in place of missing nuclear and hydro capacities demand a larger replacement, and the strategy of clean coal technology expansion is thus implemented in the scenario.

In the WR region, the first capacity of clean coal technologies is implemented from the year 2025, and more in the year 2030 onwards, effectively replacing the larger old coal fired capacities. A definite decrease in the CO_2 emissions resulting from the coal fired fleet in the region is observed starting from the year 2025, which highlight the reduced carbon intensities of these clean coal technologies. The Figure (111) compares the CO_2 emissions in the WR region in the BAU scenario with the RES+Hydro scenario (where expansions of large hydro and nuclear capacities in the WR region are not considered).

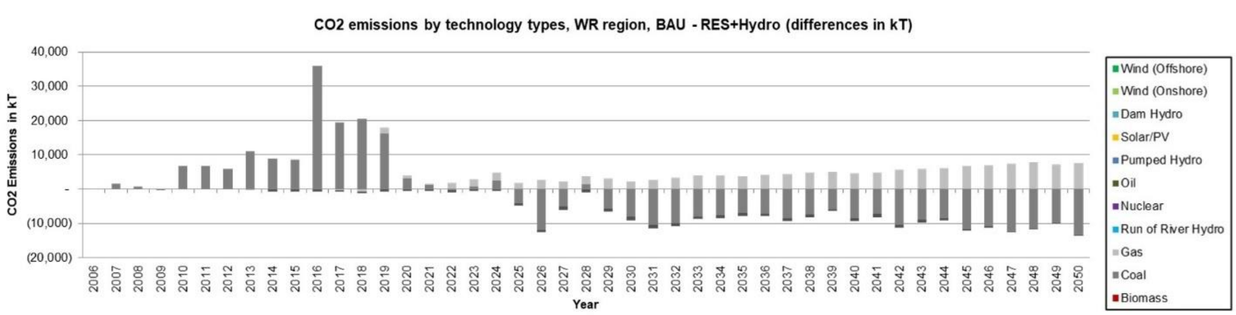


Figure (111) Differences in the CO_2 emissions resulting from electricity generation by specific technology types in the region WR, between the BAU and RES+Hydro scenario

However, in the other regions of NR and SR, due to effective hydro capacity and RES expansions in the RES+Hydro scenario, the overall emissions resulting from electricity generation in both the regions are lower, thus showing a positive difference in comparison with the RES+Hydro scenario. This doesn't mean that the clean coal technologies are not effective, they fulfill the overall obligation in the redispatch by compensating the reduced generation from specific technologies due to transmission bottlenecks in these regions, as most of the new 'clean coal' technology capacities are installed next to bigger demand centers in NR and SR. The differences in emissions in the NR and the SR regions can be seen as represented in the Figure (112).

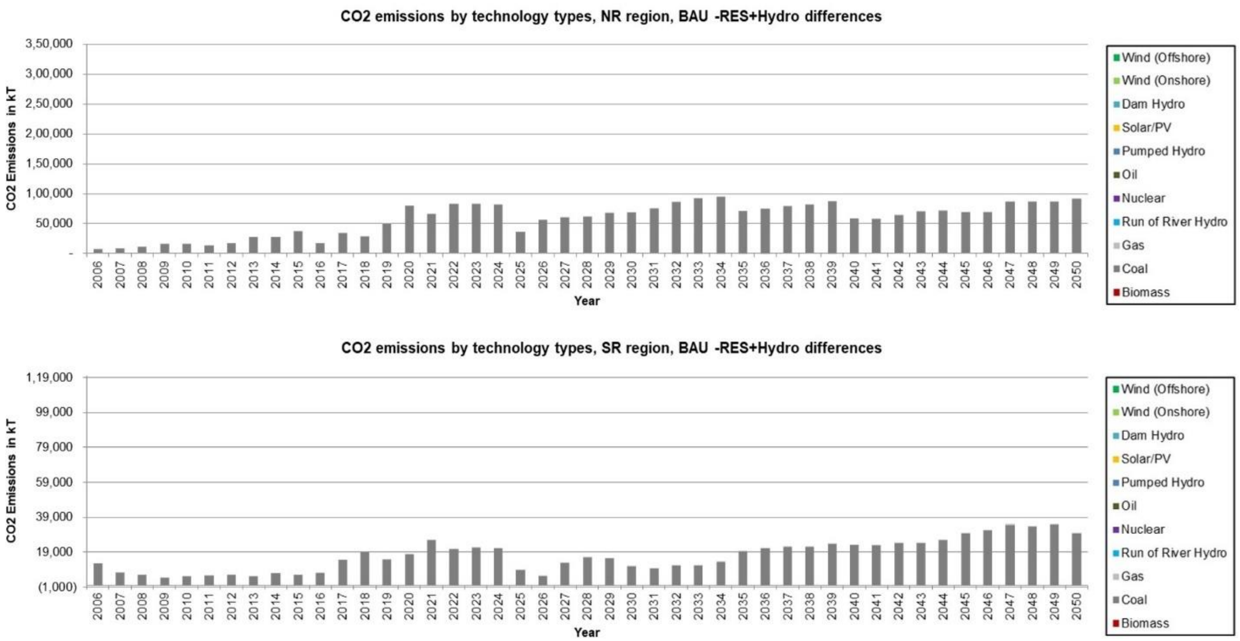


Figure (112) Differences in CO_2 emissions by technology types in the power plant fleet of the region NR (above) and SR (below) in the BAU vs RES+Hydro comparison

7.2. RES Scenario: Effectiveness of VRE expansions in specific regions

With the GoI motivated in increasing the share of solar PV- both at a utility scale and a distributed generation scale, a large expansion of VRE capacities is observed in the SR and WR regions. With potentially identified rich areas in these regions, it makes general sense to install these capacities in the above said regions. The Figure (113) gives a comparison of the solar PV, onshore wind and offshore wind capacities installed, and the yearly changes in capacity installed in the SR and WR regions.

It can be observed from the figure that both the regions have almost similar total generating capacity. The SR region has more prominent installed solar PV capacity expansion than the WR region. However, the development of offshore wind energy is much more aggressive in the WR region, while onshore wind capacities are installed more in the SR region. The energy generated by these capacities in the regions give a good quantification of the effectiveness of such capacity expansions in these regions.

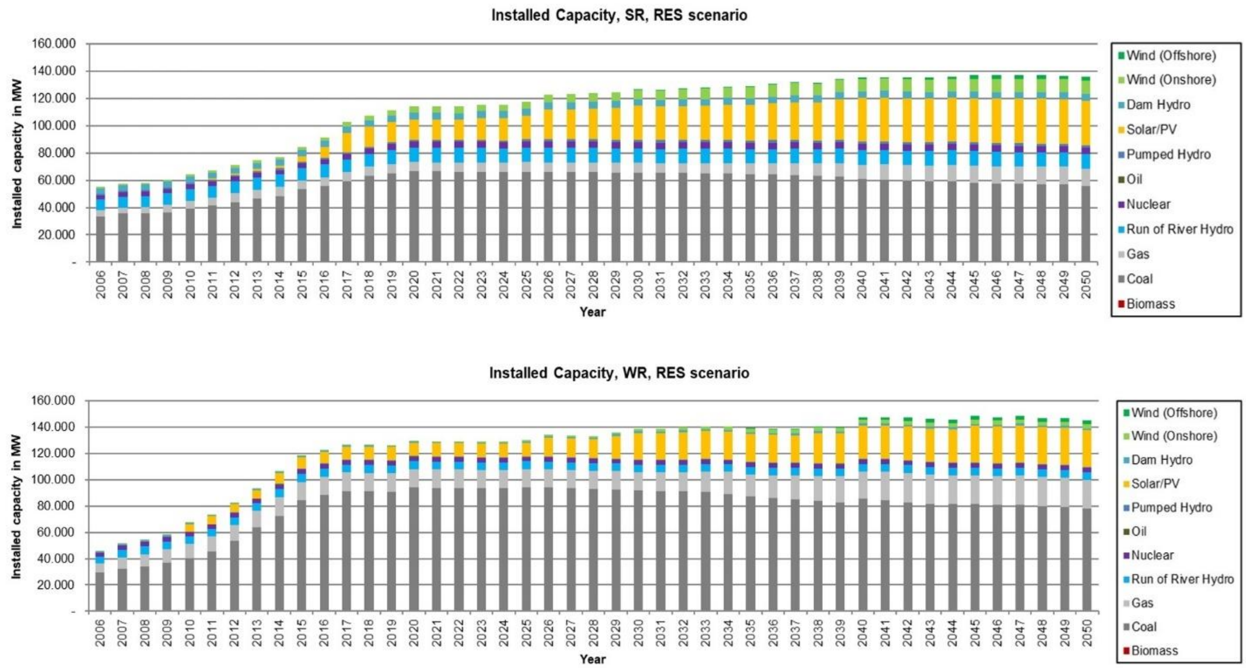


Figure (113) Installed regional capacities by generating technology type, in the SR (above) and WR (below) respectively.

The Figure (114) shows the share of electrical energy generated by specific technology types in the SR and WR regions.

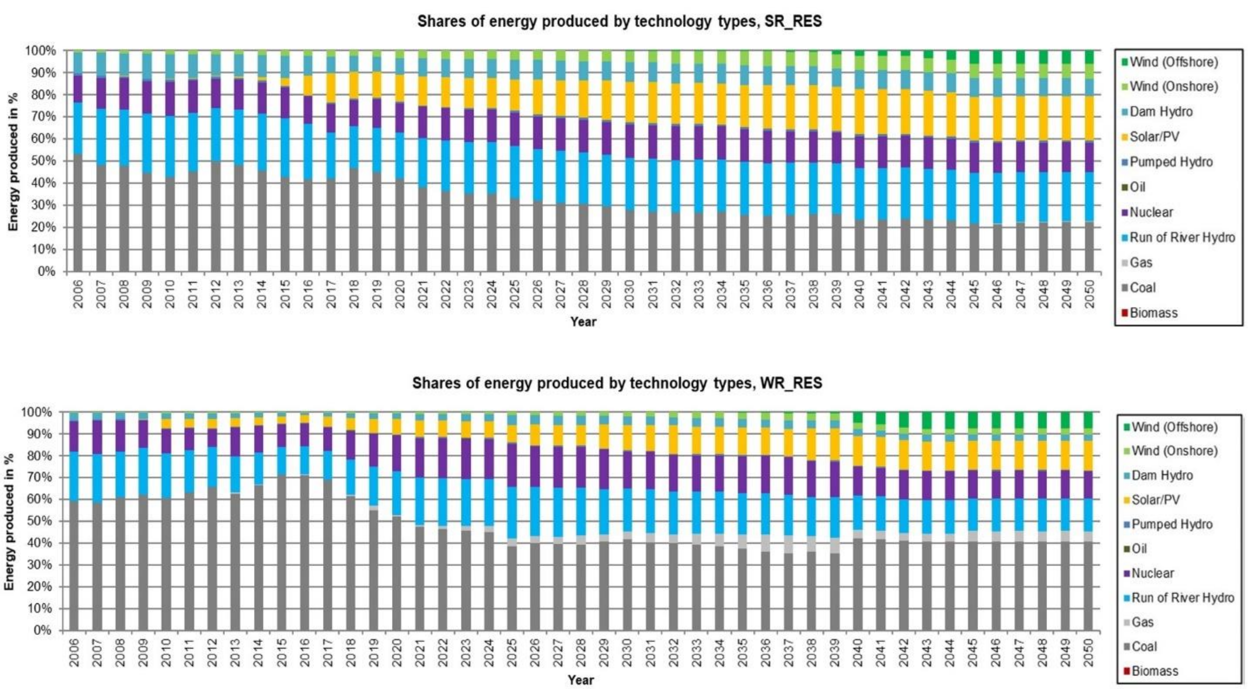
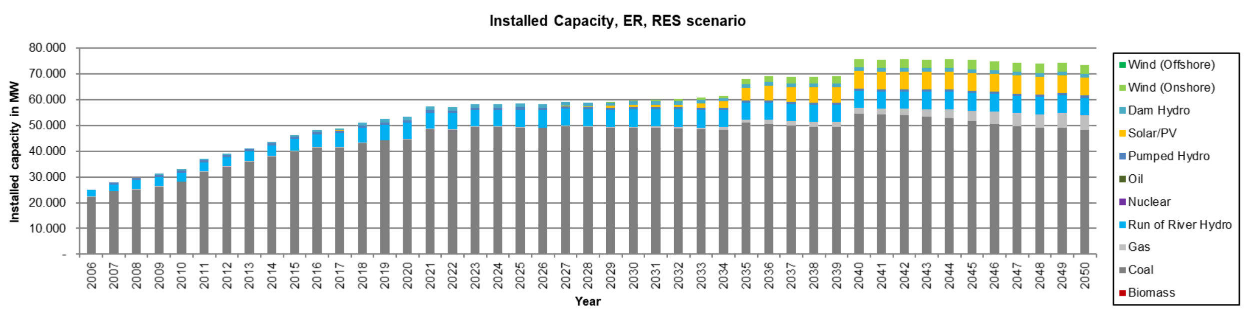


Figure (114) share of electrical energy generated by specific technology types in the energy mix of the SR (above) and WR (below) respectively.

The solar PV installations in the SR region seems to be really effective, even though the available potential and usage area being higher in the WR region. The seemingly decreased energy generated by solar PV capacities in the WR region might be a result of redispatch, with VRE technologies not connected to demand centers with sufficient transmission infrastructure. The improvement of the transmission network in the north western part of the WR region could strategically prove very useful, in the effective integration of the solar PV capacities.

The electricity generated from the 3 GW of offshore wind capacities in the WR region is seen to be really effective, as a considerable share of energy generated is observed, in comparison to the SR region. Overall, the 5 GW of offshore wind installations in both the regions prove to be really effective, considering their share of generated electrical energy in comparison with their installed capacity shares. These offshore wind capacities are also supported by new transmission infrastructure, at a higher voltage level. In the SR these transmission lines are planned in support of the proposed Th-FBR units in the southern tip of the peninsula.

Another interesting aspect of the RES expansion in this scenario is the region ER. With less than average potential (in comparison to SR and WR), the performance of the solar PV and wind capacities installed are seen to be really effective. However, with an aggressive thermal power capacity expansion, a majority of the electrical energy in the region still comes from coal and gas-fired capacities. The Figure (115) gives an illustration of the installed capacities in the ER region, along with the electrical energy generated by each technology type.



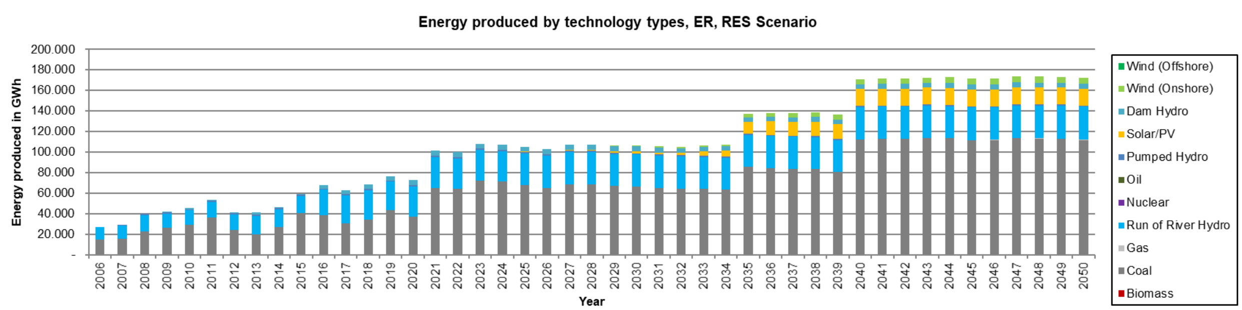


Figure (115) Installed capacity (above) and electricity generated (below) in the ER region, RES scenario

Even with a large expansion of hydro power planned in the region, the share of electricity generated by hydro power technologies remain almost the same, while the energy from thermal fired capacities increase considerably. This is mainly due to transmission congestion in the northern part of the ER, where cross border transmission happens between the regions of BH, NE, NP, NR and ER. Though specific transmission lines are planned in the region, a larger transmission capacity in the region could prove really effective. Solar PV and wind capacities installed in this region amount up to 10.5 GW, in the year 2050 from almost close to nothing in the year 2025, mainly as a part of the distributed PV strategy. These capacities prove to be really useful, as they compensate the redispatch occurring due to the congestion discussed above and generate a fairly large share of electrical energy. The VRE addition in the region could be really effective, hence a much larger capacity of VRE technologies could be planned in the region.

Finally, with a large share of hydro power capacities installed, the region NR does not show a large change in electrical energy generated from each power plant technology type. Around 25 GW of solar PV and Wind capacities are installed in the region in the year 2050. These capacities produce almost 12 percent of the electrical energy generated in the region, effectively replacing thermal power capacities – including the highly efficient CCGT replacements for old coal power plants. The Figure (116) gives a comparison of the installed capacity with the share of electrical energy generated by capacities of each power plant type in the region NR for the scenario RES. With a large available potential and desert wastelands in the western region of NR, expansion of solar PV capacity must be highly encouraged in the region.

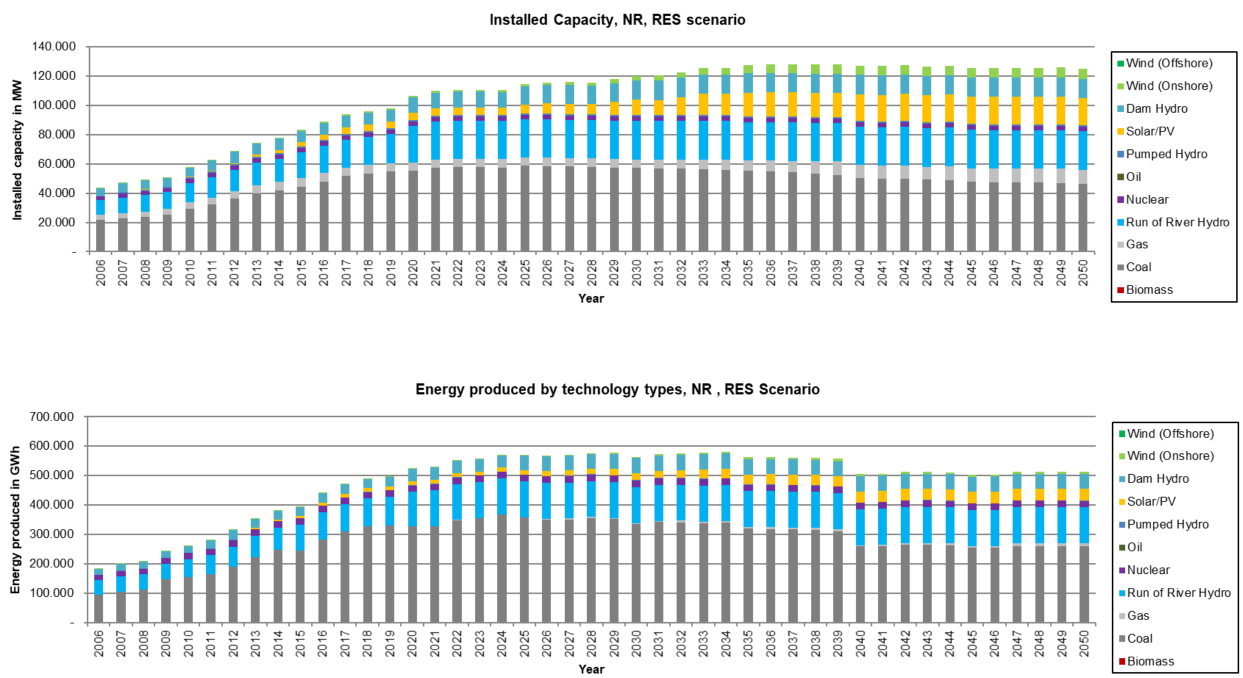


Figure (116) comparison of the Capacity mix (above) and the electrical energy mix (below) in the NR region for the RES scenario

7.3. RES+Hydro Scenario: Increased export from smaller regions

A much more detailed analysis leads to the conclusion that without a major overhaul or reinforcement of the transmission grid in the NE region, the hydro capacities planned at the region, along with the hydro power capacities in the region BH cannot be effectively integrated. One of the largest hydro potentials in the region must be planned with a seemingly good strategy. The HVDC lines planned from the NE region towards NR region prove to be highly effective, by integrating most of the hydro capacities in the NE region, turning the almost import dependent region to a major exporting region.

The Figure (117) shows the import/export balances in the NE region, resulting from the generation fleet planned in the RES+Hydro scenario. The electrical generation capability of the NE region was really low, especially in the initial years 2006-2012 due to many delayed or deferred power plant projects.

A steep growth of demand after 2018 with the subsequent increase in energy security and energy access was seen in the region and was expected to be covered by a large share of electricity from the ER and BA regions. The hydro capacities planned in these regions after 2020 turn out to be really effective in these regions by generating more than enough electricity, eventually contributing to the overall energy system in the subcontinent.

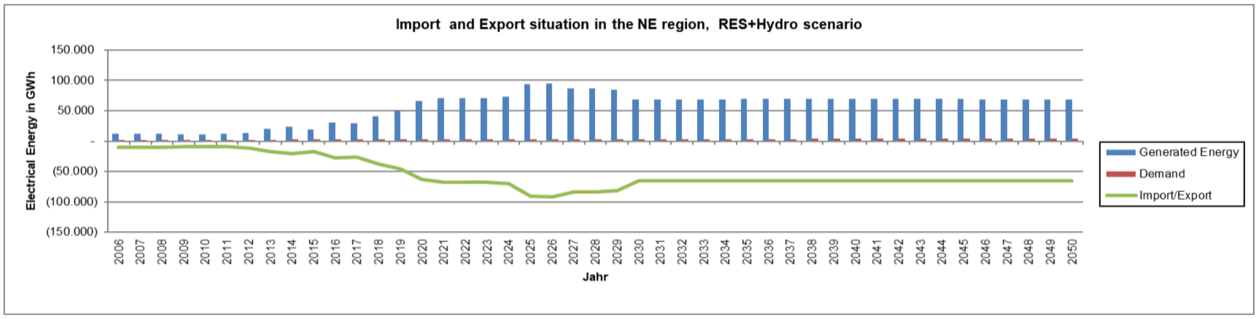


Figure (117) Import/ Export balances in the NE region, RES+Hydro scenario

Similar situations are observed in the BH and NP regions, both the regions show improved exports after the planned hydro capacities are commissioned, from the year 2020 till the year 2030. This is possible only through additional and improved cross border transmission capacities between these regions and the Indian regions of ER and NR. A major share of the electrical energy generated in the RES+Hydro scenario is from the hydro power plants in these regions.

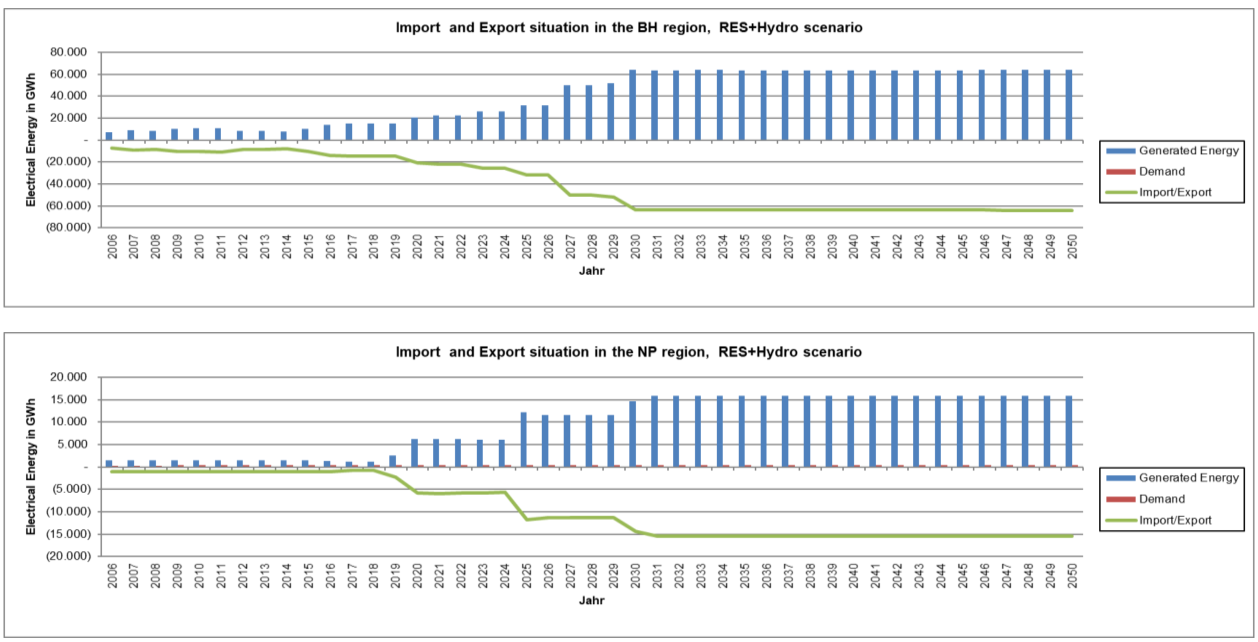


Figure (118) Import/Export balances in the BH region (above) and NP region (below), in the RES+Hydro scenario

The exports in the regions BH, NE and NP are observed to reach a limiting value after the year 2030, as NTC increase has only been implemented until the year 2030 in the simulation model scenarios. The improvement of NTC capacities, which sets a limit on the export of electrical power between these regions and demand-rich regions should be a valid strategy, by implementing larger cross border transmission capacities. With the increase of NTC, a much larger increase in export from these regions could be eventually observed.

7.4. Nuclear Scenario: Introduction of nuclear capacities in the BA and SL regions

With the India and Russia supporting the installation of over 1000 MW each of PWR capacities in Bangladesh and Sri Lanka, a large change is observed in their respective energy systems, especially in their power plant portfolios. In scenarios other than the nuclear scenario, gas fired capacities in BA and Hydro power and oil-fired capacities in SL form the largest shares in energy generation. However, in this scenario, a brief look at the regional electrical energy generated by each of the different power plant types in the BA and SL regions give a quantification of the effectiveness of the nuclear installations. Also, it was observed in the load flow visualization of the nuclear scenario that the HVDC line interconnecting the SL and SR regions is highly effective in this scenario by usage to the maximum transmission capacity. The Figure (119) shows the installed capacity mix and generated energy mix in the SL region in the nuclear scenario. The energy generated by the nuclear capacity phases out both electricity generation by oil and gas fired capacities in the SL region, which could prove really helpful as the SL region can finally break free from their dependency on oil-fired power plants, especially around major demand centers.

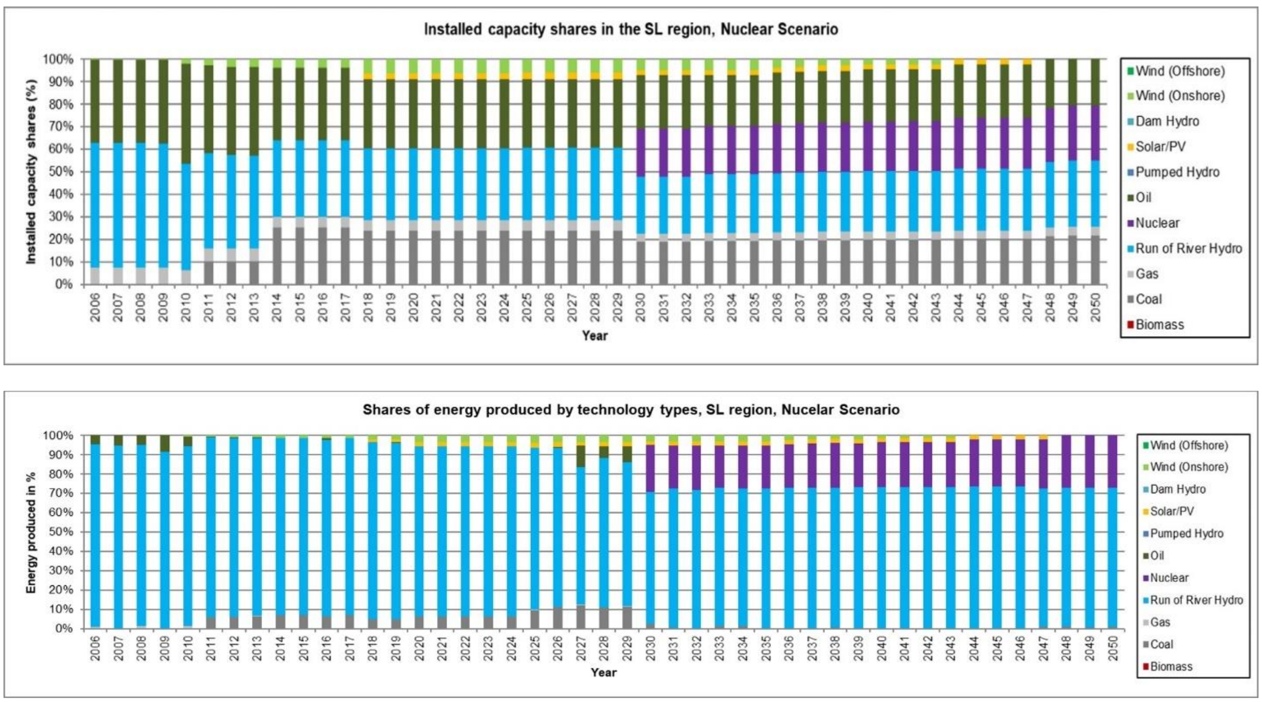
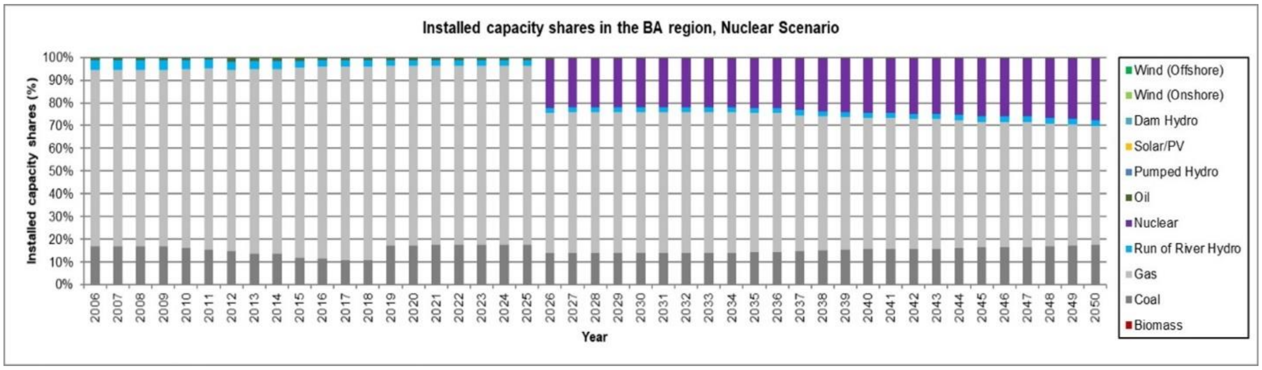


Figure (119) Capacity mix (above) and electrical energy mix (below) highlighting the share of generation technology types in the SL region, Nuclear scenario.

Considering the impacts of introducing nuclear power in the BA region, several changes can be observed from load flow visualization as seen in the results of the Nuclear Scenario. The interconnections between BA, NE and ER seem to be relatively congestion free, but the internal transmission network in the BA region shows some congestion. A comparison of the installed capacity mix and the electrical energy generated mix by different technology types in the BA region (Figure (120)) sheds light on the effectiveness of each type of installed capacity.

The electricity generated from nuclear power in BA effectively replaces electricity by a large share of gas-fired capacities, though a decreased generation is observed from the year 2036 to the 2046. These reductions in generation are invariably the result of redispatch in the transmission system in the BA region, due to insufficient transmission around demand centers. The nuclear energy share in the mix after the reinforcement of grid in the year 2046 increases to a higher extent, especially due to the higher transmission capacities of the reinforced transmission infrastructure. Thus, unlike the SL region, without a well-planned reinforcement of the grid in the BA region, the installed nuclear capacities are not completely effective.



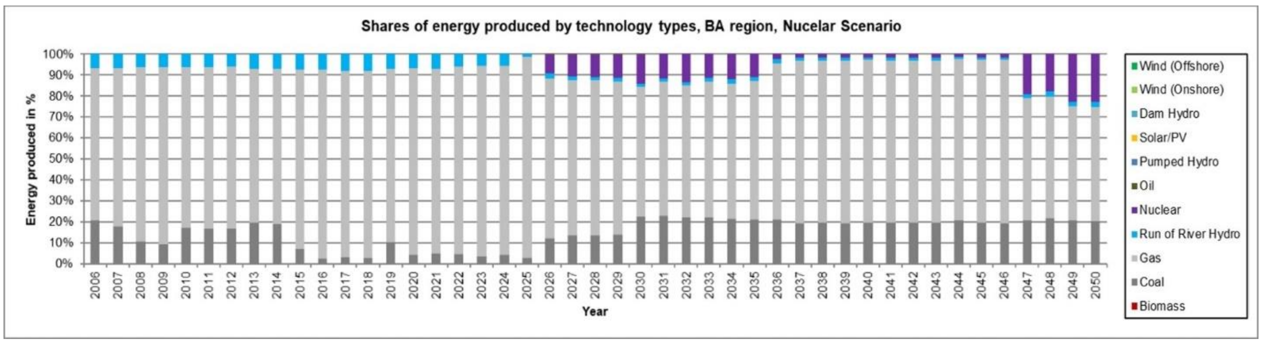


Figure (120) Installed capacity shares (above) and Electrical Energy generated shares (below) by specific power plant types in the BA region, Nuclear scenario

7.5. Capital cost evaluations

The RES+Hydro Scenario, where the hydro power capacities are added as per strategical targets defined by the governments of India, Bhutan and Nepal seems to be the most capital stock intensive scenario of the four scenarios defined. The results of the GCS and NCS calculations and their comparisons in each region give us a great deal of understanding about the economic situations in the respective regions. A short summary of the significant results of each region are as discussed.

In the NR, BH, and NP regions, the hydro power capacity expansion practically build up almost all their respective capital stocks, thus showing the importance of hydro power installations in their subsequent regions. Even though a large capacity of thermal capacities in the NR region is planned, they falter in comparison with the capital stock contribution of the regional hydro power plant fleet.

With the Indian electricity sector investing in the capacity expansions in the regions of BH and NP, the overall wealth in these regions exponentially increase due to the subsequent increase of their NCSs. These investments made by the Indian sector are based on the bilateral agreements of ownership transfer after 80 years, the regions of BH and NP get a large increase in their capital stocks without any major investments, as large technical lifetimes and lower depreciation values of hydro power plant capacities benefit the regions even after the ownership transfer.

In the WR and SR regions, thermal power forms a sizeable chunk of the capital stock share, while hydro power capacity still forms the major share in the capital stock of the respective power plant fleets. However, the thermal power contribution eventually decreases in the later years till the target year due to high depreciation values. The solar PV and wind power capacity expansions contribute in a small capacity to the build-up of the capital stock in the respective regions, in the target year 2050. These technologies have significantly lower technical lifetimes, along with higher depreciation values. They still form a large part of the required investments over the subsequent years, with larger capacities planned in the next decade.

In BA and SL regions, the gas and oil-fired power capacity expansions form a larger share in their respective capital stock shares. This could mean more capital stock intensive hydro power investments are necessary for the sustainable and long-term economic welfare in the BA and SL power sectors. Also, with the introduction of nuclear capacities in the above-mentioned region in the Nuclear Scenario, majority of the capital stock shares of these regions can be expected to shift from gas- and oil-fired capacities to nuclear capacities.

CHAPTER 5

Conclusions and Suggestions

8. Conclusions

With considerations to the simulated results and the discussions on specific results, several conclusions were taken during the thorough evaluation of the thesis. As no changes to transmission infrastructure were assumed between all the defined scenarios, the major conclusion on which scenario would suit the electricity system the best was taken on the basis of the level of power plant fleet diversification, the effectiveness of the installed capacity, and the amount of emissions resulting due to the generation of electricity by the specific power plant fleet. The investigation of all the three parameters point in the direction of the scenario effectiveness, and aids in the strategic development of the electricity system in the Indian subcontinent region.

8.1. Diversification of power plant portfolio

The measure of diversity in power plant portfolio is a measure of a good strategy, as power plant technology types are mostly found to complement each other in the complex interplay observed in the electricity system. The complementation of performance of various power plant types usually removes the manual effort required to balance the electricity system. In the case of high VRE penetrations in electricity systems, the resulting integration costs can be significantly reduced, with the support of additional DRE technologies.

Though every scenario other than the BAU scenario have their fair share of electricity generation technologies, the highest level of complementary power plant portfolio diversification was observed in the RES+Hydro scenario. In this scenario, a large share of DRE technology types like run of river, dam and pumped storage hydro installations are considered along with a seemingly large but not aggressive expansion of VRE technology capacities like solar PV and Wind power plants. The nuclear power plant capacity also plays a vital role in the power plant mix, as steady electricity generation options.

8.2. Installed capacity and generated electrical energy

The effectiveness of the installed capacities could be quantified with the comparisons of installed power capacities and their shares in the total electricity generated, along with the load flow analysis of the existing transmission network. Even in this evaluation, the RES+Hydro scenario proved to be more effective in accommodating the VRE capacities when compared to the RES scenario, where a large share of VRE capacities are installed in potentially rich areas with higher full load hours. Though the regional impacts of the RES scenario are more prominent and better than the RES+Hydro scenario, the effectiveness (in terms of generated electricity and power plant performance) of the power plant fleet in the overall model region is the main goal in the thesis.

The VRE capacities in the RES scenario are observed to be underperforming, especially due to the limited transmission infrastructure around the respective feed in nodes. With the inclusion of new lines and the suggested reinforcements in the transmission network, the resulting performances of these capacities would probably vary.

8.3. Transmission system and power plant performance

The observed values of change in generation due to transmission bottlenecks gives us a measure of the significance of the performance of transmission infrastructure between the generation and consumption nodes. By comparing the redispatch differences in power plants mainly resulting from the bottlenecks in the transmission system, it was observed that a majority of the VRE capacities show positive redispatch differences (more generation) in the RES+Hydro scenario in comparison with the RES scenario. This brings us to a conclusion that the VRE fleet in the RES+Hydro scenario is integrated in to the grid in a much more effective way than in the RES scenario. With reference to the redispatch generation differences in the power plant fleet defined in the RES+Hydro scenario, the logical reasoning would be that the increased DRE shares in the power plant fleet support the generation of VRE capacities in the fleet.

8.4. CO_2 emissions from electricity generation

Finally, the RES scenario was naturally found to be the scenario with the least amount of calculated CO_2 emissions with a large difference of over 100 million tonnes of CO_2, in comparison with the RES+Hydro scenario. However, it was observed that the RES+Hydro scenario results in the second least CO_2 emissions, considerably lower than the nuclear and the BAU scenarios.

With the capital stock calculations in mind, the social and economic welfares in the relatively economically poor regions of NP and BH must also be considered, when co-existence is a major factor for the sustainability of the electricity in the region. It was observed that in the RES+Hydro scenario, the regions of BH and NP have a considerable boost in the evaluated wealth of their electricity system, with significant investments made from the Indian power sector. This increase in capital stock could easily and definitely bring about economic and social welfare in the region.

8.5. Market Price evolution

The zonal prices in the previously cheaper regions are observed to increase, while the zonal prices in the more expensive regions are seen to slightly decrease or saturate in almost every scenario. These observed increases/ decreases in the zonal prices also give us an evaluation of the profitability of investments in the subsequent model regions. The cheaper regions like BH and NP profit the most in increased prices due to trade with higher price regions.

The overall market price in the subcontinent region is observed to follow an increasing trend, with cumulative increased investments until the year 2035, and then observed to slightly decrease in the RES and RES+Hydro scenario, and a saturation in the BAU and Nuclear scenarios. The saturation of market price is mainly because of the saturating fuel prices defined in the fuel price projections. With an integrated sub-continental grid, cheaper regions are observed to profit more, with a significantly larger/increasing market price.

8.6. Overall Inference and conclusion

All the following conclusion leads to one important inference – The RES+Hydro scenario is the best-case scenario defined in the course of the thesis. Along with the proposed expansion of its solar PV and wind capacities, it would be in the best interest of not only India but the overall sub-continent region to implement a much-improved strategy of expansion of run-of-river, dam, and pumped hydro capacities in the regions where there are already observable potentials – the BH, the NE and the NP regions.

With increasing market prices, and low zonal prices, the BH, NE and NP are found to profit subsequently throughout the simulation timeline, all the while enduring positive re-dispatch differences in solar PV and wind capacities installed in the other Indian regions. Increasing the cross-border capacities and having a better NTCs between these regions and the other seems to be the best possible and sustainable improvement to the electricity system in the subcontinent region.

Though the CO_2 emissions resulting in the RES+Hydro scenario are significantly higher than the RES scenario, with strategically planned transmission infrastructure and large hydro capacities, the RES+hydro scenario could achieve much lower overall emissions.

The assumptions considered for building scenarios in the thesis regarding the implementation of the energy efficiency standards in the region should be assigned the highest priority, as the only way to stop the continuously increasing electricity demand in the region would be to implement these minimalistic efficiency standards.

9. Future research and further improvements

A research project is never completely finished, only concluded due to specific time and effort restrictions. The development of ATLANTIS_India from the beginning has seen continuous developments in almost all regions, from the input model data structure to the optimization of market mechanisms. In this section, further possible and suggested improvements to the model ATLANTIS_India are mentioed.

- ATLANTIS_India can be further improved by the introduction of various new technology types like power generation from waste, biogas units and many others, adding further possibilities of new technology-based energy strategies in the Indian Sub-Continent region.

- The detailed and accurate energy analysis of the regions BA, BH, NP and SL and their transmission network becomes absolutely necessary, as it was found both in published records and in this thesis that there will be higher interactions between the respective power regions and the Indian power sector. The exact values of the transmission line parameters could further increase the accuracy of the model, to further explore redispatch possibilities.

- The electricity systems of China, Myanmar and Pakistan could also be analysed, and regardless of the political situation between the countries, the possibility of a common interconnected, interdependent and a sustainable electricity system can be explored.

- The natural gas networks in the model regions could also be evaluated, bringing in a new dimension to the energy analysis in the sub-continent region. Energy storage becomes a much more vital issue, with the integration of such a large capacity of VRE technologies, and P2X technologies could be integrated based on the findings in the gas network analysis.

- Additional demand resulting from e-mobility charging strategies discussed by the GoI for implementation after 2025 could also be included in the model simulations, as a previous study showed an increase in peak loads in specific Indian model regions, in the range of 2 percent – 15 percent.

- Further macro-economic scenarios with different regional economic parameters could be explored, to find and compare the effects of national economic development and policies on the electricity sector. The integration of the input/output analysis [63] could provide a whole macroeconomic dimension to the model ATLANTIS_India.

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B. Abbreviations used

€, EUR: Euros
₹, INR: Indian Rupees
$, USD: Dollars (United States)

A

AC: Alternating Current
AT&C: Aggregate Technical and Commercial

B

BA: Bangladesh
BAU: Business As Usual
BEE: Bureau of Energy Efficiency, India
BEV: Battery operated Electric Vehicle
BH: Bhutan
BIP: Brutto Inlands Produkt (German)
BRICS: Brazil, Russia, India, China and South Africa
BWR: Boiling Water Reactor

C

CB: Cross Border
CC: Combined Cycle
CCGT: Combined Cycle Gas Turbine
CCS: Carbon Capture and Storage
CEA: Central Electricity Authority, India
CERC: Central Electricity Regulatory Commission, India
CHP: Combined Heat and Power
CO2: Carbon Di-Oxide
COP21: 21st Conference Of the Parties, Climate Change Conference Paris 2015
CPS: Current Policies Scenario, International Energy Agency

D

DC: Direct Current
DC-OPF: Direct Current Optimal Power Flow
DC-Opt: Direct Current Optimization
DER: Dispatch-able Renewable Energy
DisCom: Distribution Company
DSM: Demand Side Management
DSO: Distribution System Operators

E

EIA: Energy Information Administration
E-mobility: Electromobility
ENTSO-E: European Network of Transmission System Operators for Electricity
EoE: Energy only Exchange

EPR: European Pressurized water Reactor
ER: East Region
ESSO-INCOIS: ESSO Indian National Centre for Ocean Information Services
ETS: Emission Trading System
EU: European Union
EV: Electric Vehicle

F

FAME India: Faster Adoption and Manufacturing of Electric and hybrid vehicles in India
FOWIND: Facilitating Offshore Wind in India

G

G2V: Grid to Vehicle
GCS: Gross Capital Stock
GDP: Gross Domestic Product
GHG: Green House Gas
GIS: Geo Information System
GoI: Government of India
GT: Gas Turbine
GW: Giga Watts
GWh: Giga Watt Hours
GWp: Giga-Watt Potential
GWEC: Global Wind Energy Council

H

HEV: Hybrid Electric Vehicles
HT-FBR: High Temperature Fast Breeder Reactor
HVDC: High Voltage Direct Current

I

IC: Internal Combustion
IEA: International Energy Agency
IEO: India Energy Outlook
IEX: Indian Energy Exchange Limited
INDC: Intended Nationally Determined Contribution
IRENA: International Renewable Energy Agency

K

kms: kilometres
KSB: Shorting lines
kV: kilo Volts
kW: kilo Watt

L

LCoEg: Levelized Cost of Electricity generation
LCoEs: Levelized Cost of Electricity storage
LCV: Light Commercial Vehicles
LED: Light Emitting Diode
LES: Large-scale Energy Storage

M

m: meters
MCP: Market Clearing Price
MNRE: Ministry for New and Renewable Energy, India
MoP: Ministry of Power, Government of India
MW: Mega Watts
MWh: Mega Watt Hours

N

NAPCC: National Action Plan for Climate Change
NCS: Net Capital Stock
NE: North East Region
NEMMP: National Electric Mobility Mission
NHPCL: National Hydro Power Corporation Limited, India
NISE: National Institute of Solar Energy, India
NIWE: National Institute of Wind Energy, India
NP: Nepal
NPT: Non-Proliferation Treaty
NR: North Region
NSG: Nuclear Suppliers Group
NTC: Net Transfer Capacity
Nuc_BWR: Nuclear, BWR
Nuc_Candu: Nuclear, CANDU
Nuc_EPR: Nuclear, EPR
Nuc_Th_FBR: Nuclear, Thorium FBR

P

PHEV: Plug-in Hybrid Electric Vehicle
PPP: Purchasing Power Parity
PST: Phase Shifting Transformer
PV: Photo Voltaic
PWR: Pressurized Water Reactor
PXIL: Power Exchange India Limited

R

RDZP: Re-Dispatch Zonal Pricing
RE: Renewable Energy
RES: Renewable Energy Sources
RPO: Renewable Purchase Obligations

S

SDG: Sustainable Development Goals
SEZ: Special Economic Zones
SL: Sri Lanka
SR: South Region

T

T&D: Transmission and Distribution
TPEM: Technology Platform for Electro Mobility
TSO: Transmission System Operator

TWh: Tera Watt Hours

U

UK: United Kingdom
UMPP: Ultra Mega Power Plant
UN: The United Nations
UNFCCC: United Nations Framework Convention for Climate Change
UPS: Uninterrupted Power Supply systems
US: United States

V

V2G: Vehicle to Grid
VRE: Variable Renewable Energy

W

WEO: World Energy Outlook
WR: West Region

X

xEV: x- (technology type) Electric Vehicle

Z

ZP: Zonal Pricing

C. Equations

(E1) Efficiency Calculation formula
(E2) Economic welfare maximization function
(E3) Supply cleared criteria
(E4) Demand cleared criteria
(E5) Trading restriction based on NTC
(E6) Trading criteria based on technical criteria
(E7) Energy balance criteria
(E8) AC active power flow equation
(E9) AC reactive power flow equation
(E10) Impedance calculation
(E11) Series Impedance calculation