

## **Supergrid Modelling And Risk Assessment For The Indian Subcontinent**



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## **List of Abbreviations**

1. VSC: Voltage Source Converter
2. PLF: Plant Load Factor
3. WAPDA: Water and Power Development Authority
4. KESC: Karachi Electric Supply Company
5. IPP: Independent Power Producers
6. SPP: Small Power Producers
7. LCC: Line Commutated Converters
8. GIL: Gas Insulated Cables
9. CSC: Current Source Converter
- 10: IGBT: Insulated Gas Bipolar Transistor
- 11: PWM: Pulse Width Modulation
- 12: PCC: Point of Common connection
- 13: HVDC: High Voltage Direct Current

## **Abstract**

The Indian subcontinent is facing a massive challenge with regards to energy security in its member countries, the challenge of providing a reliable source of electricity to facilitate development across various sectors of the economy and thereby achieve the developmental targets it has set for itself. A highly precarious situation exists in the subcontinent that is observed in the series of system failures leading to system collapses-blackouts most of the times. To mitigate the issues related with energy security as well as to keep in check the increasing supply demand gap, a possible solution is the deployment of an interconnected electricity ‘supergrid’ designed to carry huge quanta of power across the sub-continent as well as providing the infrastructure for Renewable energy sources (RES) generation. Thus the supergrid can not only provide energy security but also boost trading and thereby ease the cross border tensions that impede growth in the subcontinent.

This paper assesses the need and conditions for a supergrid deployment and proposes a meshed topology based on VSC HVDC converter technology for the supergrid modeling. The second part of the paper evaluates, ranks and maps the key risk factors facing the supergrid deployment in the sub-continent. The key risks are then categorized in a risk map that provides a strong visual narrative for further strategic discussions to make the supergrid deployment a reality.

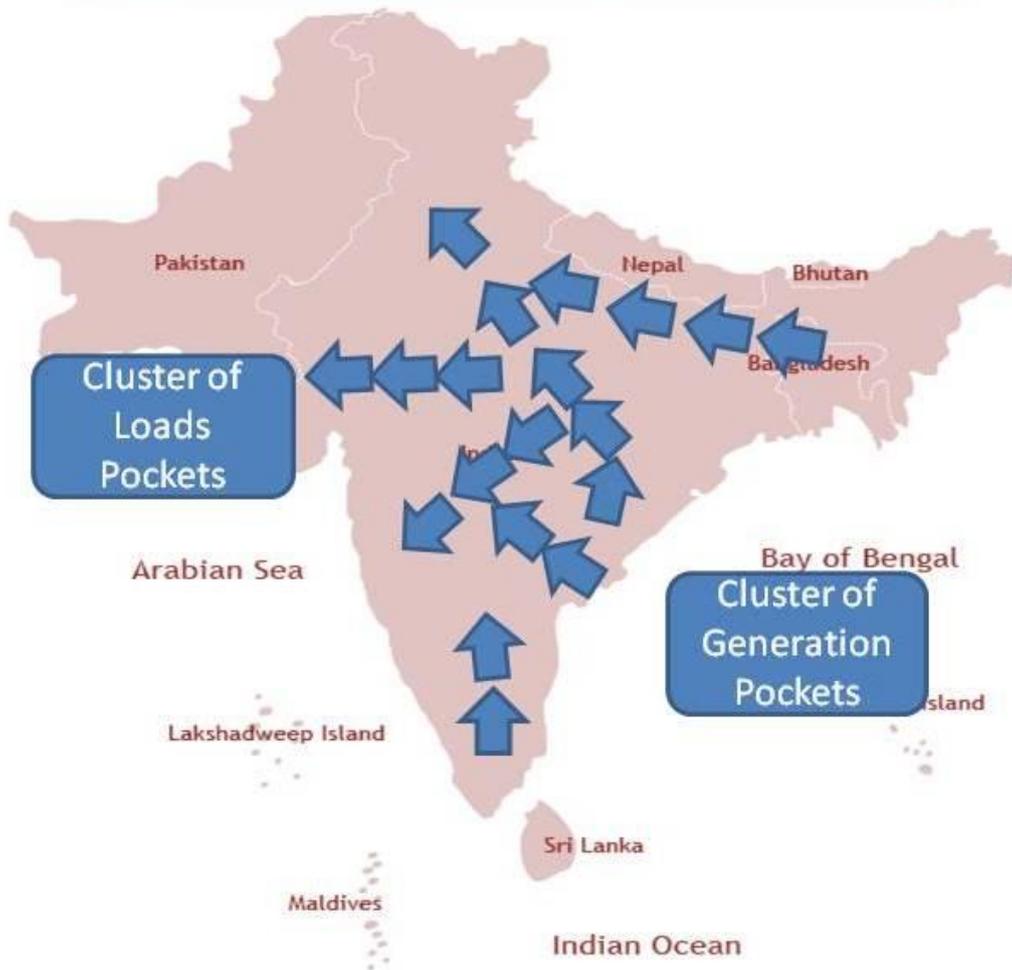
**Key Words:** VSC HVDC, Supergrid, Renewable Energy Integration, HVDC Circuit Breakers, Dynamic Energy Storage, Load Flow Analysis

## **1. Introduction:**

Climate change activism as well as a limited access of primary conventional fuels is setting the platform for a subtle shift to a sustainability centric, CO<sub>2</sub> neutral energy system. In this transformation, renewable energies as well as the formation of energy corridors for transport of the clean energy will play an important role. A great potential of renewable energy has been estimated in the Indian subcontinent. Large amounts of wind and solar energy have been estimated in some parts of the subcontinent while as others have a high potential for biomass and hydro. Procurement and hence integration into the grid of such a vast potential requires the deployment of an integrated supergrid that spans across international boundaries into neighbouring countries of the Indian subcontinent. Such an integration of the huge quantum of energy into a grid that transcends borders is one of the great challenges of this century. Moreover what sets this challenge apart is bringing the measures of technical quality and power supply reliability as well as the maintenance of stability in the same frame with economic and ecological aspects.

Dynamic energy storage will play a pivotal role in the meshed grid energy systems in order to balance the time imbalances between supply based production and a requirement based consumption. A huge energy potential has been estimated in areas not in immediate proximity to future consumption or load centres and hence need high voltage corridors to connect them to the already existing power focal points. Transport of electrical energy will require the unbundling of electricity generation and distribution depending on the politically motivated factors related to electricity deregulation. The established power corridors can provide a reliable supply of electricity based on the transmission of huge amounts of controlled conventional power over large distances in times of high demand and low supply from local focal points which are actually the local energy centres. Advances in the technical, political and regulatory underpinnings involving power intensive energy transport is necessary to see a large interconnected South Asian energy market endowed with large amounts of variable as well as conventional electricity providing reliable, sustainable and a superior quality of electricity across the Indian subcontinent. Hence on a local scale, large structural modifications have to be carried out for the imminent changes.

## Creation of transmission highways from generation pockets to load pockets in India



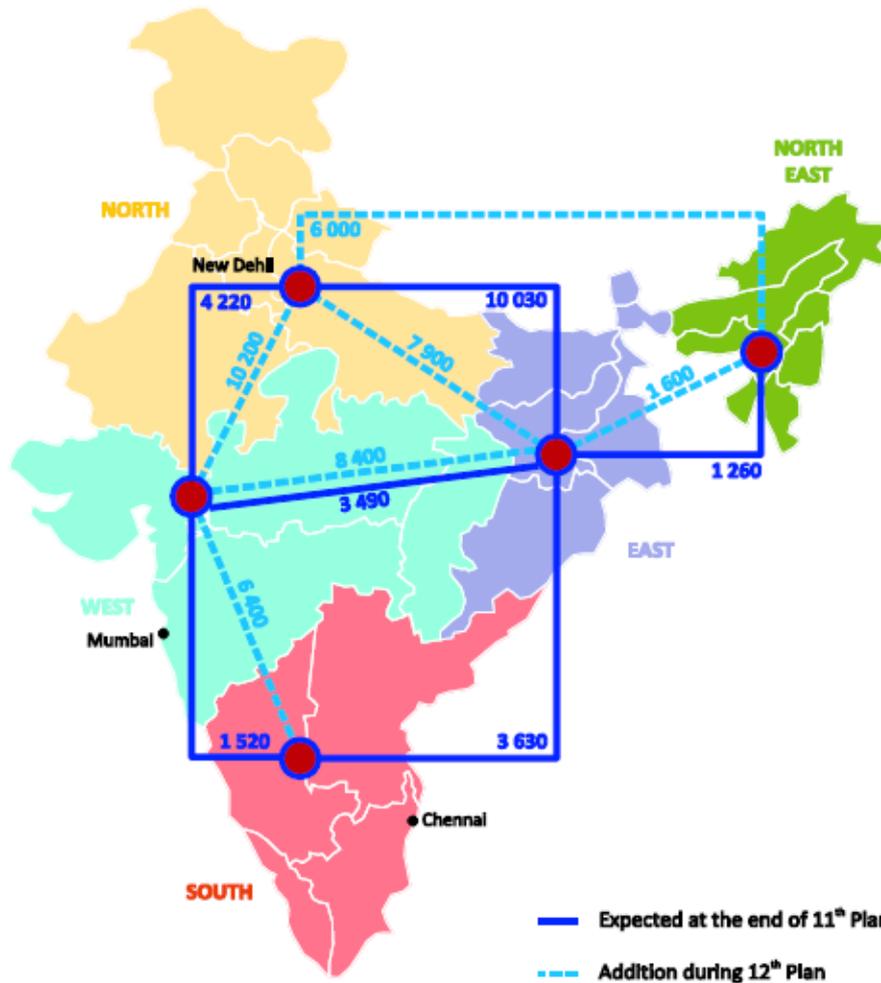
**Figure1: Creation of transmission highways from generation to load pockets in India**

**Source:** Author, Data obtained from Wikipedia.org

Transmission and thus making available this huge quantum of power at the super nodes (high power buses) requires the development of high voltage energy corridors that have the capability to transfer this bulk energy in a reliable and most efficient way. These energy corridors are an interconnected network of extra high voltage transmission lines. Economics of grid deployment in addition to efficient transmission have to be taken into

account while designing and deploying these corridors. Moreover social protocol in addition to technical orientation has to be respected for specifying the technology used.

**Existing and planned transmission networks expansion in 12<sup>th</sup> Five-Year Plan (MW)**

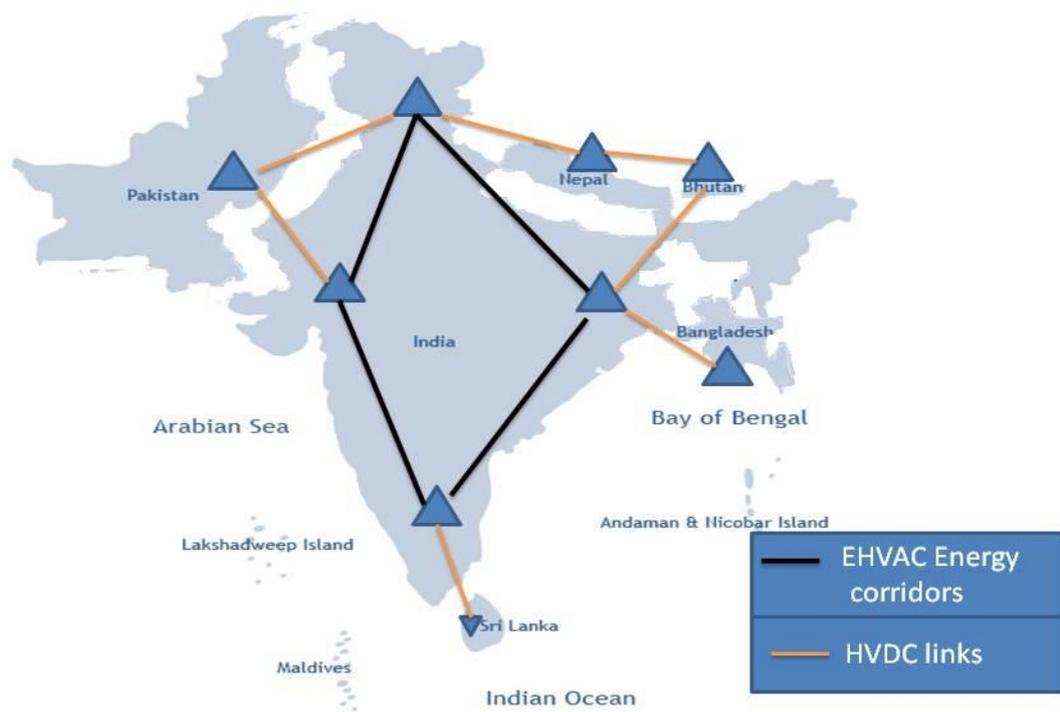


**Figure2: Existing and planned transmission networks expansion in the 12<sup>th</sup> five year plan (MW)**  
**Source:** India Electricity Grid Interconnection Report

Consequently the application of a supergrid in the Indian Subcontinent that is basically a high voltage energy transmission system mainly working on the high voltage DC transmission will provide the required platform to connect the five countries to a sustainable and abundant energy resource as well as providing an energy market for the free trade of electricity in the international market. Electricity has to be deregulated and treated as a

commodity that is supplied without qualitative differentiation across a market<sup>1</sup>. International trading of electricity provides the consumers the opportunity to be exposed to a higher quality of electricity and enables competition in the local market thus leading to regulations in the price of electricity. The supergrid thus leads to an interconnection of national energy markets and completely transforms the way electricity is produced, transmitted and consumed in the subcontinent. The main benefits envisioned from the supergrid deployment are:

- Introduction of an element of resource diversification bringing energy security
- Introducing energy corridors so as to promote the import and export of electricity between nations
- Reduction of regional isolation
- Promoting member states to forage into the field of renewable energy
- Harmonising and unifying the electricity market in the Indian subcontinent



**Figure 3: Creation of energy corridors connecting the regional grids as well as the grids of the member countries.**

[Farhan Beg 2014]

<sup>1</sup> <http://en.wikipedia.org/wiki/Commodity>

## **2. Holistic Assessment of Supergrid deployment**

The supergrid deployment in the Indian subcontinent as proposed in this research has been done by a multi-dimensional approach in which certain key levels were identified. Given the magnanimous scale and complexity of the deployment of such an infrastructure, there was a strong need for a detailed analysis of various parameters involved. But additionally we address the requirements and the participation percentage of the member countries involved. While as this research provides a technical perspective of the deployment of such a project, it would be unrealistic not to cover certain other key parameters involved as well. To get an idea of the complex nature of various key factors that play a role in the supergrid deployment, a risk assessment has been done. Serious efforts have been made to explain the position and magnitude of the risks involved. Risk assessment in addition to modelling of the supergrid in the subcontinent is instrumental in addressing the dynamic nature of the research methodology involved.

The supergrid deployment involving the introduction of a high voltage energy corridor provides a multi-pronged solution to the transition from a high carbon conventional interconnected infrastructure to a more sustainable smart infrastructure that links the national grids of the member countries. A need based assessment of various countries has been done to provide the policy makers with an idea as to how the supergrid deployment can, to a large extent take care of the supply shortfalls as well as the unrelenting increase in the demand. Moreover the following discussions can also help to assimilate and provide a working model after 30 years in the Indian subcontinent where huge stresses on the national grids often lead to system/grid failure.

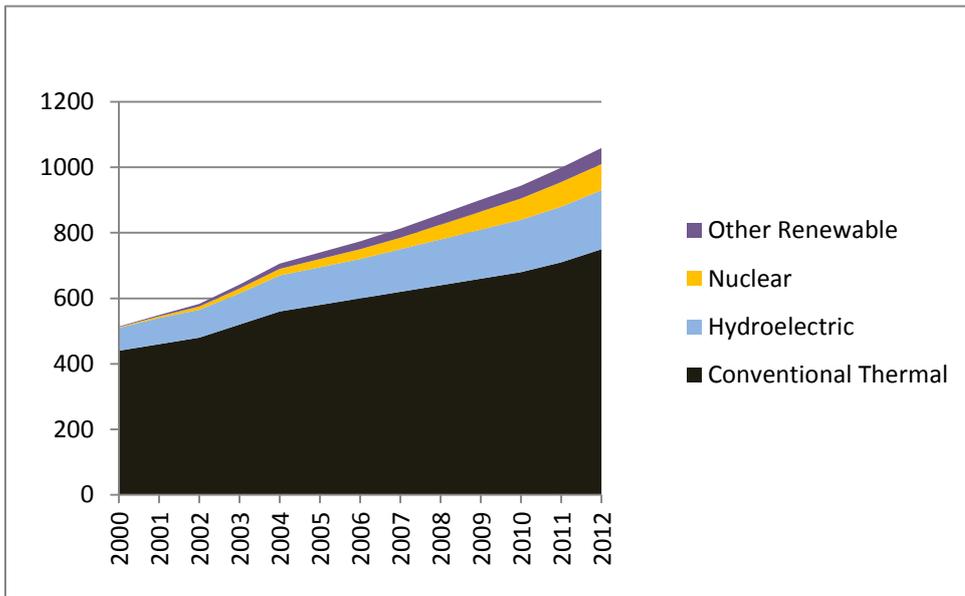
### **2.1. Energy scenario in the Indian subcontinent**

The Indian subcontinent provides totally different scenarios in different parts because of the large area it encompasses. Many factors such as climate, natural resources, topography, population and economy result in a subtle shift from one scenario to another across borders. The supergrid can to a large extent bring stability and a balance with respect to energy security in the sub-continent. This consequence can be a working factor for the supergrid deployment. A country-wise need and scope assessment has been done in the subsequent

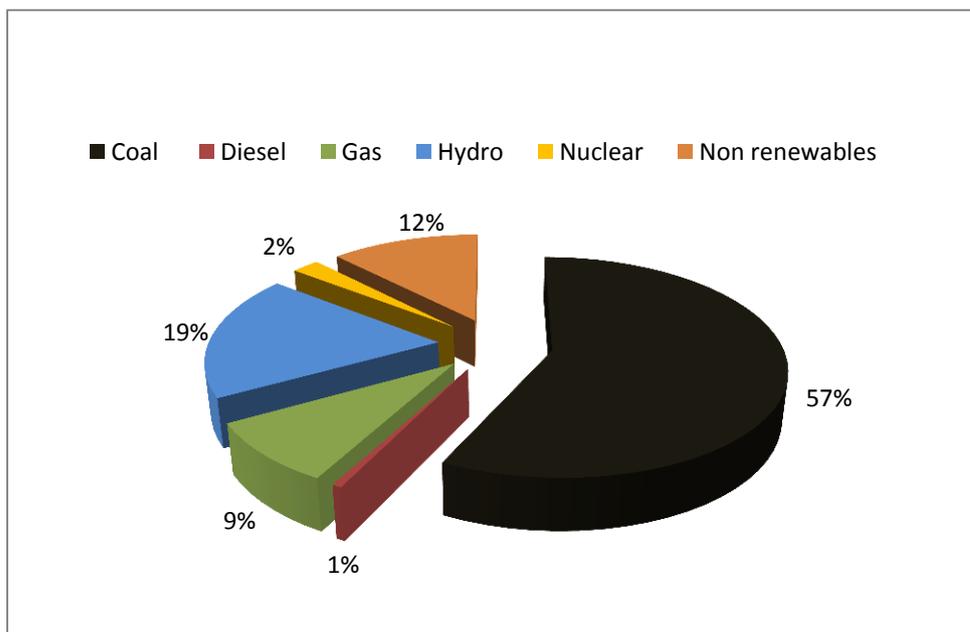
research. This assessment is quantitative based on the data obtained from various electricity regulatory agencies and hence provides a working platform for the discussion on the supergrid deployment.

### **2.1.1. Energy Scenario of India:**

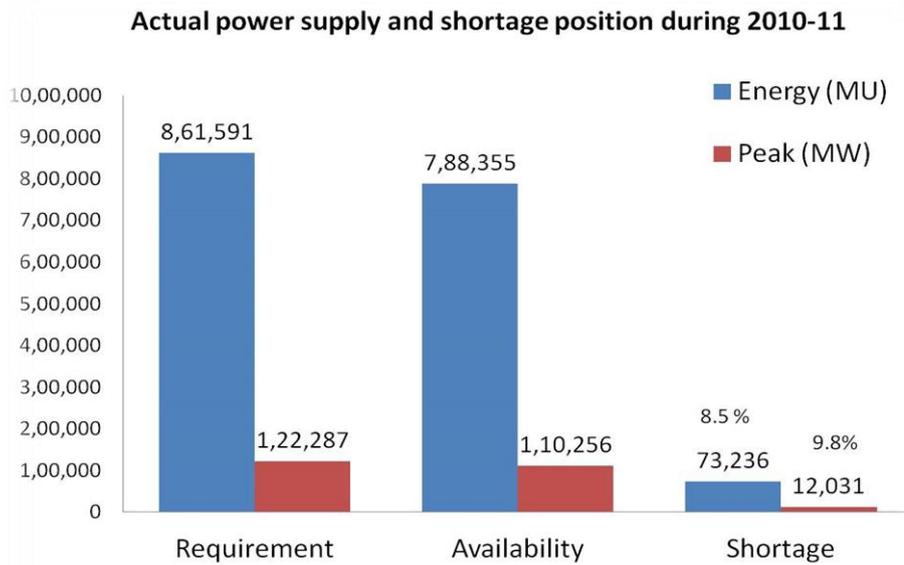
India had an installed power generation capacity of 210 GW as of November 2012, which is about 154 times the installed capacity in 1947 (1362 MW). Electricity demand has been consistently outstripping the supply even as power availability has increased due to significant investments on the supply side. India faces the challenge of poor reliability and a poor quality of electricity, leading to frequent load shedding's in the country. Procurement of coal is a very serious issue in the country with many coal fields reaching the maximum point of production and thereby further extraction is depleting. Shortage of coal at many generating sites is resulting in a low efficiency process leading to the stations working at moderately to very low plant load factors (PLF's). Moreover refining and extraction of the local coal is not going on at a level that could cope up with the coal utilisation factor of the generating stations. Import of gas from gas rich countries is a highly uneconomical and non-feasible at this time. Even though the geographical location of the country provides a very high scope for the country to utilise sustainable energy from wind and sun there is a general consensus that upgrading the traditional generation network from conventional won't be enough for the country to match the phenomenal growth in electricity consumption. In all renewable energy fronts, India is currently ranked 5th in the world. With a total generating capacity from renewable sources being about 30 GW, mostly obtained through wind (18.3GW), small hydro (3.4GW), biomass (1.2GW) and solar (1GW). The main renewable energy sources in India are wind energy, solar energy, biomass and waste and hydro energy.



**Figure 4: India Electricity generation from different sources**  
 [Farhan Beg 2014] Data obtained from the EIA



**Figure 5: All India Installed capacity (as on 30<sup>th</sup> November 2012)**  
 [Farhan Beg 2014] Data obtained from Monthly Reports CEA December 2012



**Figure 6: Power Supply and Shortage position during 2010-11**  
**Source:** Central Electricity Authority annual report.

## 2.1.2 Energy Scenario of Pakistan

Pakistan's per capita/year energy use is 12.7 MMBTU compared with 65 MMBTU/capita/year for the world<sup>2</sup> each for hydro and nuclear.<sup>3</sup> The power situation in Pakistan remains to be one of the most severely criticized services rendered by the government of Pakistan. Load shedding and power outages are a common scene every day. Electricity generation, transmission and distribution runs under the auspices of two vertically integrated (PSUs) public sector utilities: Water and Power Development Authority (WAPDA) and the Karachi Electric Supply Corporation (KESC). Around 20 independent power producing companies contribute significantly in the field of electricity generation in Pakistan. The Pakistan Atomic Energy commission was set up to oversee the country's vast experience with nuclear fuel. Two nuclear power stations running satisfactorily in the country are Chesnuup and Keenuup.

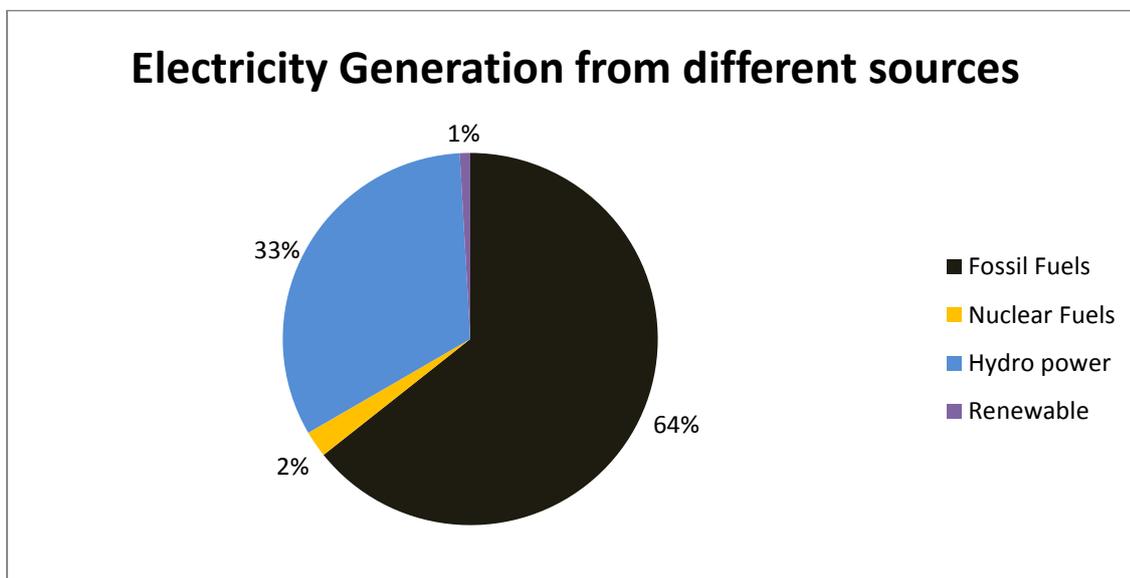
The supergrid can to a large extent provide Pakistan with a reliable electricity system involving electricity integration from the renewable energy sources as well as energy imports

<sup>2</sup> Ahmad, Gulfaraz, Peace and Prosperity Gas Pipelines, United Nation Development Program, 2003.

<sup>3</sup> World Energy Outlook 2006, International Energy Agency, Paris, France

from neighbouring countries. The Pakistan grid can be directly connected to the northern and western grids of the Indian subcontinent via HVDC links leading to a more dynamic and extensive grid. Electric power can be easily transferred across the border via DC links and thereby making the Pakistan national grid strong and resilient, providing a reliable power supply to its populace. Moreover the supergrid can also provide the basic structure required for the integration of huge amounts of renewable energy into the national grid.

For the purpose of this research, the Sindh Valley that is located in the South of Pakistan and West of India has been identified as a Wind energy potential source. A potential of around 150 GW of wind energy has been estimated in Pakistan out of which nearly 40 GW is estimated in the Sindh valley. This untapped source of energy can be integrated into the grid only if the grid is dynamic and resilient enough to deal with the issues of instability because of variability of energy sources and unpredictability. Even though this research paper does not encompass a power flow analysis/load flow analysis of the energy integration from the Sindh-Valley into the supergrid, a draft model of the supergrid showing the connections between the Sindh valley and Pakistan and India has been made. The research for the power flow analysis is currently underway.



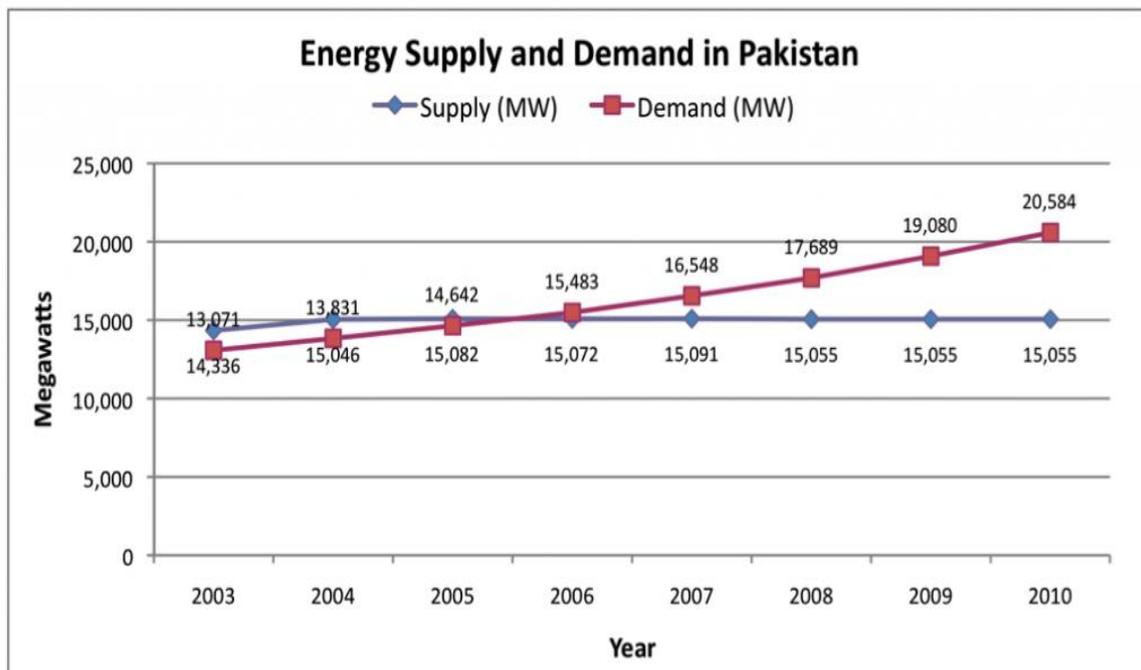
**Figure 7: Electricity generation from different sources in Pakistan**

**Source:** EIA energy assessment report for Pakistan



**Figure 8: Location of the Sindh Valley in Southern Pakistan**

Source: Wikipedia, Regions of Pakistan



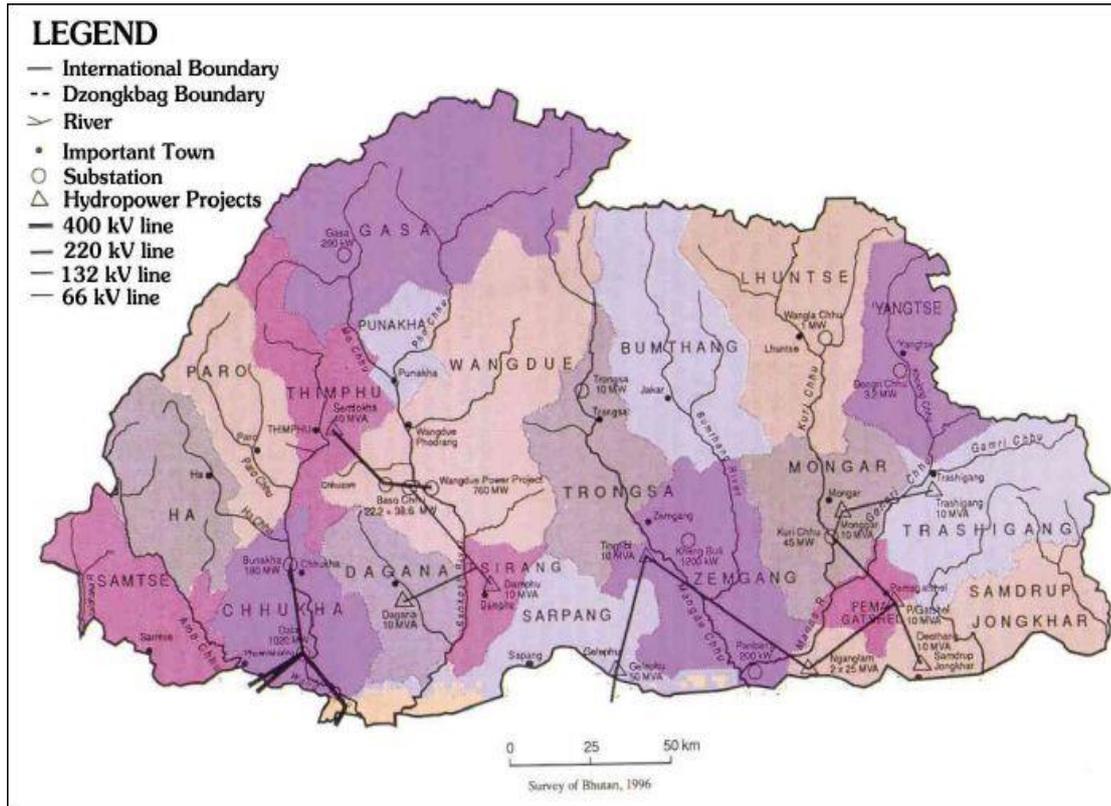
**Figure 9: Energy imbalances in Pakistan**

Source: EIA Annual Report, Energy trends

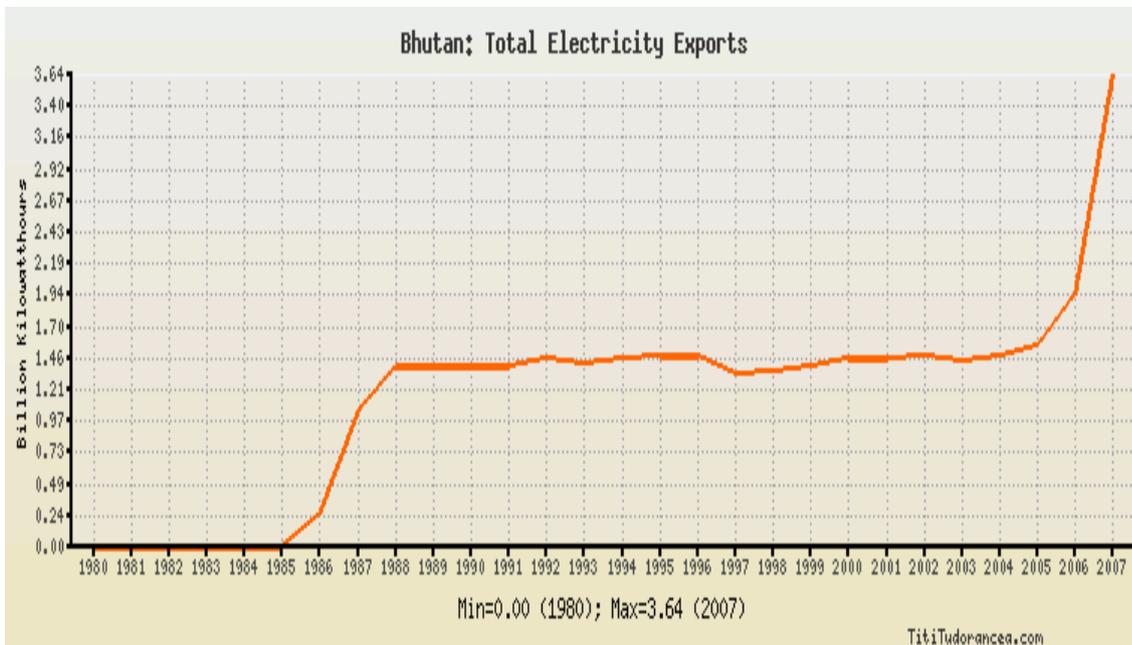
### **2.1.3 Energy Scenario of Bhutan**

Bhutan is a relatively small country lying in the eastern Himalayas with Thimpu as its national capital. Bhutan is landlocked between China in the North and India in the other three directions. Occupying an area of nearly 38394 sq. km it is inhabited by approximately 650,000 people. As of 2012, only about 70 percent of the total households had access to grid connected electricity. Banking on the national goal of providing electricity to the whole country by 2020, Bhutan has set for itself ambitious strategies to tap all the Hydro resources. The potential of hydropower in the country is enormous to not only satisfy its domestic demand but also export the electricity to India and China. This can be made possible by a highly efficient grid infrastructure that has the capability of transporting bulk energy across the borders into the neighbouring countries. Even today, hydropower remains the pivotal source of foreign revenue that is obtained by Bhutan with an average share of annual national income of 60 percent in 2009.

With the commissioning of the 1020 MW hydroelectric power station that was completely financed by India in 2006 the total generation of the country tripled. However this represents only 5 percent of the total hydroelectric potential of the country estimated at 30 GW. Bhutan like any other third world country is going through a phase of rapid development backed by the foreign exchange obtained through the sale of hydroelectric power. This development is leading to an improvement in the quality of life and transforming Bhutan into an energy intensive country. Bhutan currently exports more than 75 percent of its generated hydroelectricity to India. This export leads to an income and thus the streamlining of foreign exchange which is used to meet Bhutan's other goals. There is a strong need of the introduction of dynamic energy policies geared towards two mandates, that is, providing quality, affordable and reliable energy to its populace as well as quantifying electricity as an export service leading to an increased revenue sharing from foreign trade.



**Figure 10: Bhutan International and National Borders with transmission levels knowledge**  
 Source: Bhutan Energy Grid, [www.geni.org](http://www.geni.org)

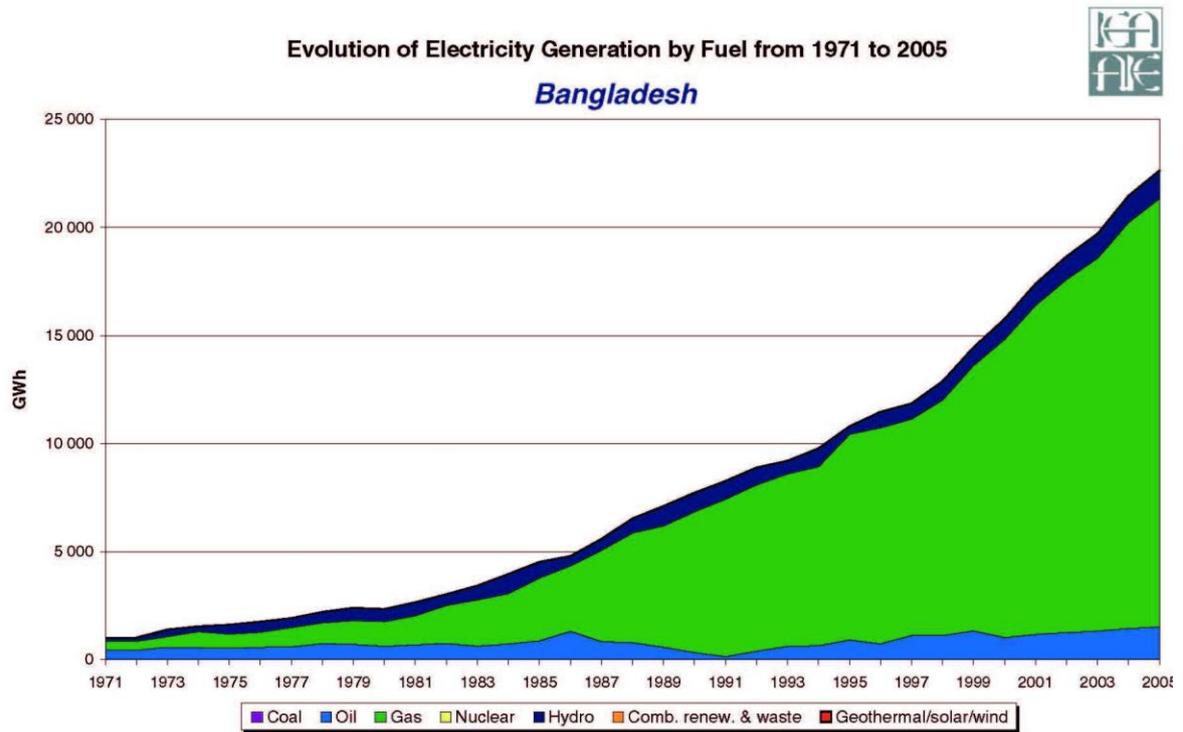


**Figure 11: Bhutan Electricity Exports**  
 Source: [www.tititudorancea.com](http://www.tititudorancea.com)

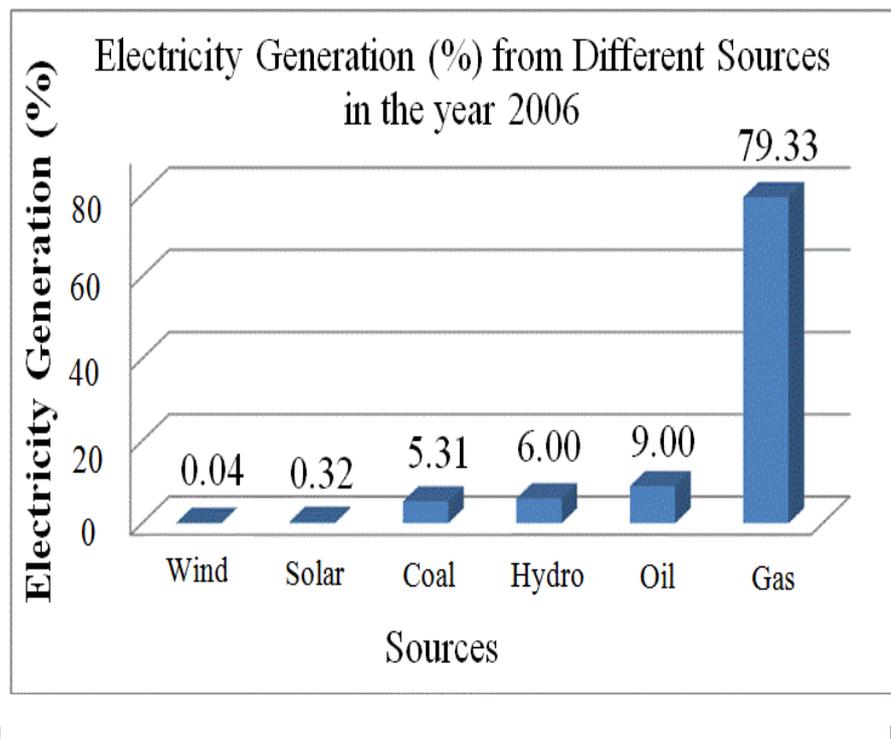
## **2.1.4 Energy Scenario of Bangladesh**

Bangladesh, officially the People's Republic of Bangladesh, is a sovereign state in the Indian subcontinent. It is located at the apex of the Bay of Bengal, bordered by India and Burma (Myanmar) on its north, west and east, and separated from Nepal and Bhutan by India's narrow Siliguri corridor. Together with the neighbouring Indian state of West Bengal, it makes up the ethno-linguistic region of Bengal.

The total installed capacity was 4005 MW in the financial year 2000-01 which has increased to 6685 MW in FY 2010-11 with an annual increasing rate of 6.62 percent. Continuation of this rate indicates that the projected generation would be 4828 MW by 2015 which is far shy from the vision of 11500 MW generations by 2015. Although the government has taken several initiatives for reducing the deficit of electricity, the crisis persists. This is mainly due to the problems associated with high gas dependency, improper privatization policy, lack of satisfactory and timely implementation of allocated money, political reasons and overpopulation. Bangladesh depends heavily on the availability of gas for its generation of electricity. The government of Bangladesh has failed to ensure a secure supply of gas to its generating station thereby leading to low plant load factor's (PLF) and hence very low efficiency. On the other hand, failure to ensure a stable coal policy has also proved detrimental in the generation sphere. Quick rental and peaking plants were taken on a fast track basis to address the nagging power crisis. But mostly, second hand equipment and machineries are used in such plants, which are less efficient and the tariff rises. The unstable political sphere of the country has negatively affected the country's generation industry because of the failure to set up and implement a secure and a dynamic energy policy. The country faces a significant challenge in revamping its grid network responsible for the transmission of electricity. Therefore, such policy formulations must be done based on the results of realistic and practical research regarding the power sector. A credible and realistic demand forecast is necessary because of its strategic location, import of electricity from Bhutan and India using high voltage energy corridors can mitigate the energy shortages present in the country.



**Figure 12: Evolution of Electricity Generation by Fuel from 1971 to 2005**  
Source: [www.geni.org](http://www.geni.org)

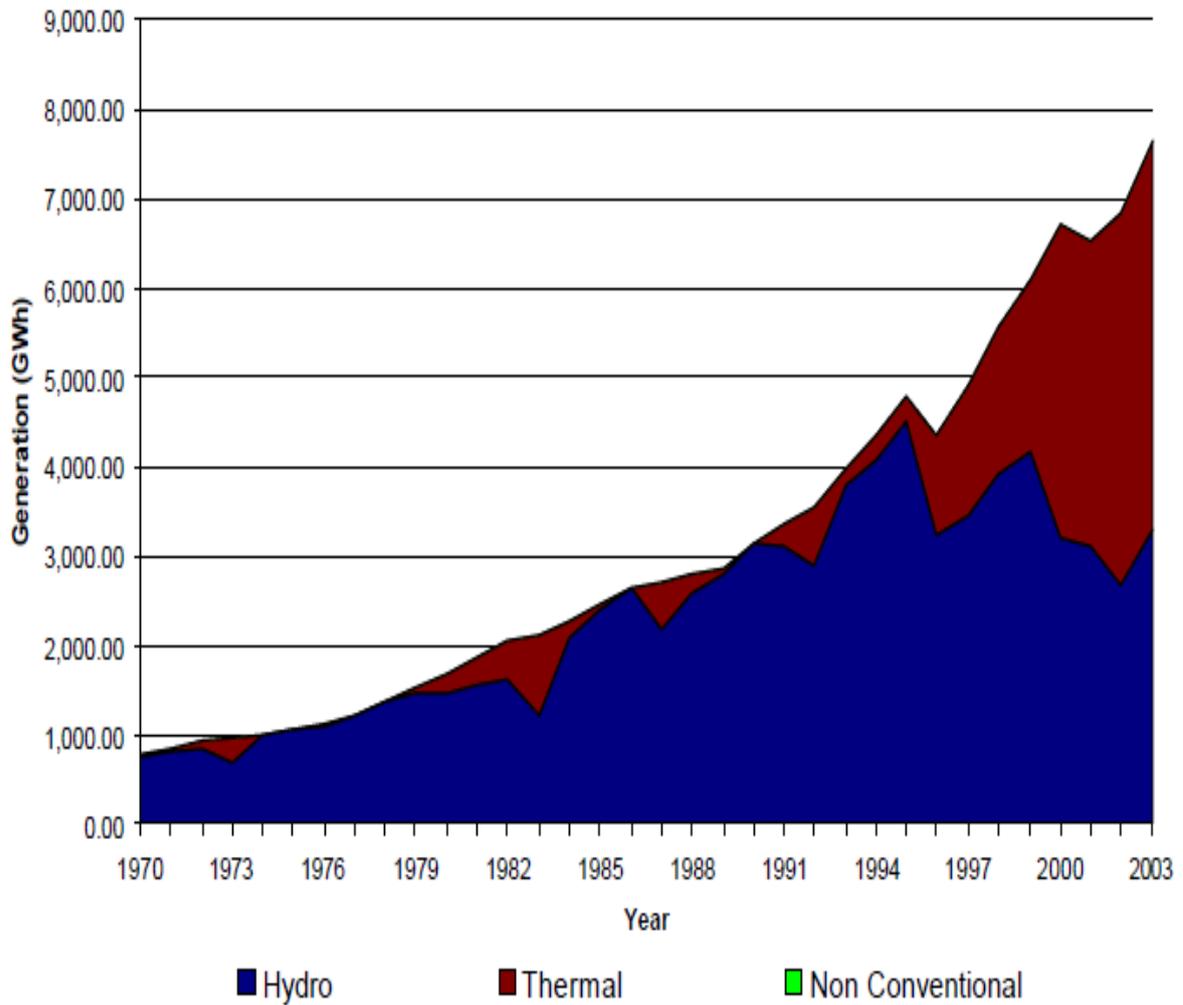


**Figure 13: Electricity Generation from different sources in the year 2006**  
Source: [www.engj.org](http://www.engj.org)

### **2.1.5 Energy Scenario of Sri Lanka**

Sri Lanka, officially the Democratic Socialist Republic of Sri Lanka, is an island country in the northern Indian Ocean off the southern coast of the Indian subcontinent in South Asia. Popularly called as “Ceylon” until 1972, Sri Lanka has maritime borders with India to the northwest and the Maldives to the southwest.

Electricity needs in Sri Lanka are met mostly by generating electricity using petroleum based thermal sources and hydro based generation. Most of the hydro potential has already been harnessed and thus Sri Lanka will need to use the petroleum based thermal sources for generation until other generation capacity is also introduced. Sri Lanka has total identified hydro power potential of 2 GW out of which nearly 1.5 GW has already been harnessed. The government has shown a general interest in pursuing additional and cost effective sources for the generation of electricity. This comes as a consequence to reduce the widening supply-demand gap and reliance on hydro power. This output is dependent on the water levels and sink to very low levels in times of drought. Diesel fired and fuel oil can provide a fairly useful avenue as a possible short term solution while as coal based power generation can be the most effective source of power generation in the future. In 2011, the maximum recorded electricity demand in Sri Lanka was 2163.1MW. In order to achieve that demand and to cater the electricity requirement in Sri Lanka, 139 Grid connected power plants with total installed capacity of 3140MW were operating in 2011. Out of those power plants, 23 were owned and operated by Ceylon Electricity Board including 16 hydro plants, 6 thermal plants and 1 wind power plant.



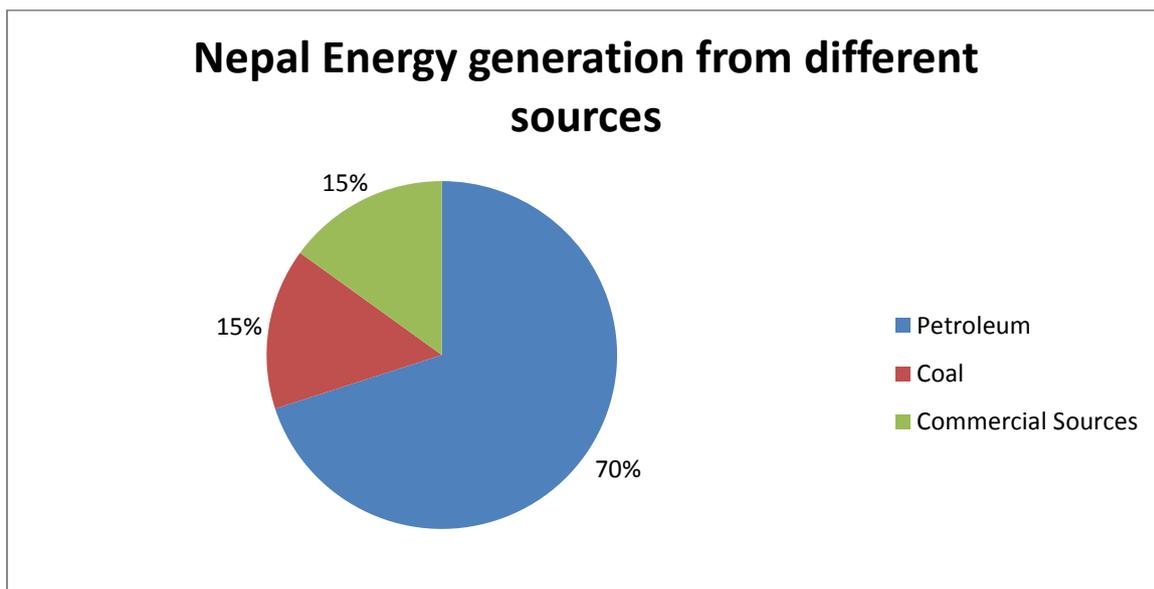
**Figure 14: Variation in Electricity generation distribution from different sources in Sri Lanka from 1973 to 2003**

[Farhan Beg 2014] Data from the Ministry of Power, Sri Lanka

## 2.1.6 Energy Scenario of Nepal

Biomass and hydropower are two indigenous and high potential energy sources in Nepal. Fuel wood supplies nearly 80 percent of the cumulative energy demand. Yet it is extracted quite dangerously beyond the sustainable capability of the forests to supply the wood, thus driving efforts towards deforestation. The country has a potential of nearly 83000 MW of Hydro-electricity out of which only about 280 MW has been developed. Nepal does not utilize this electricity potential it supplies only about ten percent of the total energy consumption. Nepal has huge renewable energy resources, but most of the rural populations rely on the traditional use of biomass, which causes increasing rate of deforestation and negative impact on health due to indoor pollutions. Furthermore to collect the traditional fuel the poor households spend long hours on cooking and household chores. This reflects in lost opportunities for self-improvement and family well-being through the betterment of social and economic status.

The current energy crisis in the country with huge renewable energy potential shows the chronic imbalance between energy consumption and energy resource endowment. At present only around 1.5% (613.5 MW) of feasible hydropower potential (32000 MW) has been developed yet and around 40 percent of the total population has some form of access to electricity. Commercial energy includes fossil fuels and electricity. Fossil fuels are mainly imported from India except small amount of low quality coal production in western part of the country. Electricity is mainly produced from hydropower.



**Figure 15: Nepal Energy generation from different sources**

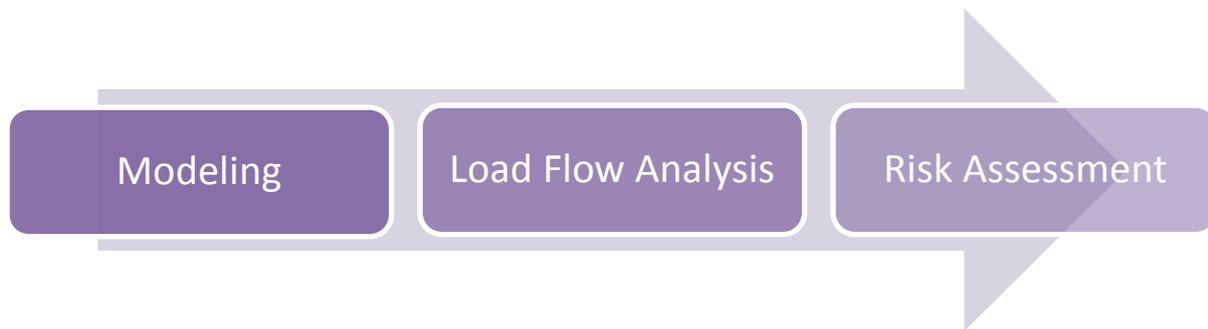
[Farhan Beg 2014] Data from the EIA

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### **3. Methodology of deployment of an interconnected Supergrid:**

In the search for a stable and a reliable power infrastructure with an ability to bring energy and financial stability in the subcontinent, a supergrid is by far the most viable solution. By connecting supply chains to load centres using enhanced control, the supergrid offers a comprehensive solution to the issue of energy instability. Moreover the geographical spread of such an infra-structure introduces a huge variety to energy portfolio available and thereby increasing the security of supply. Supergrid deployment involves certain issues that pose a serious hurdle in its conceptualisation. While as the technical portion can be engineered by utilising the idea of a meshed smart grid system, the actual deployment in the subcontinent brings with it some potential risks that need to be studied separately. Thus the deployment must address the technical and the regulatory issues separately.

Modelling of the supergrid has been done comparatively in which the most feasible technology available has been shown to provide the links and nodes of the supergrid. Potential generation sites as well as potential load centres have been anticipated while applying the concepts of power losses due to transmission and distribution networks. This analysis comes under the heading of “modelling of the supergrid in the sub-continent” and conceptualizes the transformation of connecting different nodes via high voltage energy links. The key risks before the deployment and consequent development of a supergrid are non-technical. An assessment, evaluation and ranking of the various non-technical risks involved has been done in the topic “risk assessment for the supergrid deployment” highlighting the risk items that are likely to impact the power sector throughout the development of the Supergrid. The risk assessment concludes with the formulation of a risk map that will provide a strong visual aid in understanding the effects of the key risks involved.



**Figure 16: Methodology of Supergrid deployment**  
[Farhan Beg 2014]

### **3.1. Modelling of the supergrid:**

The basic need for the introduction of the supergrid is to provide an electricity highway for the flow of electric power between nations. This will provide a capability to interconnect the asynchronous transmission systems of the subcontinent in order to efficiently control the exchange of seasonally varying production and storage capacities. The supergrid involves a planned approach towards grid modernisation taking into account the interconnection between unsynchronized grids as well as being equipped to integrate and distribute the huge renewable potential of the subcontinent. There are different considerations for the structure and type of technology for the energy corridors.

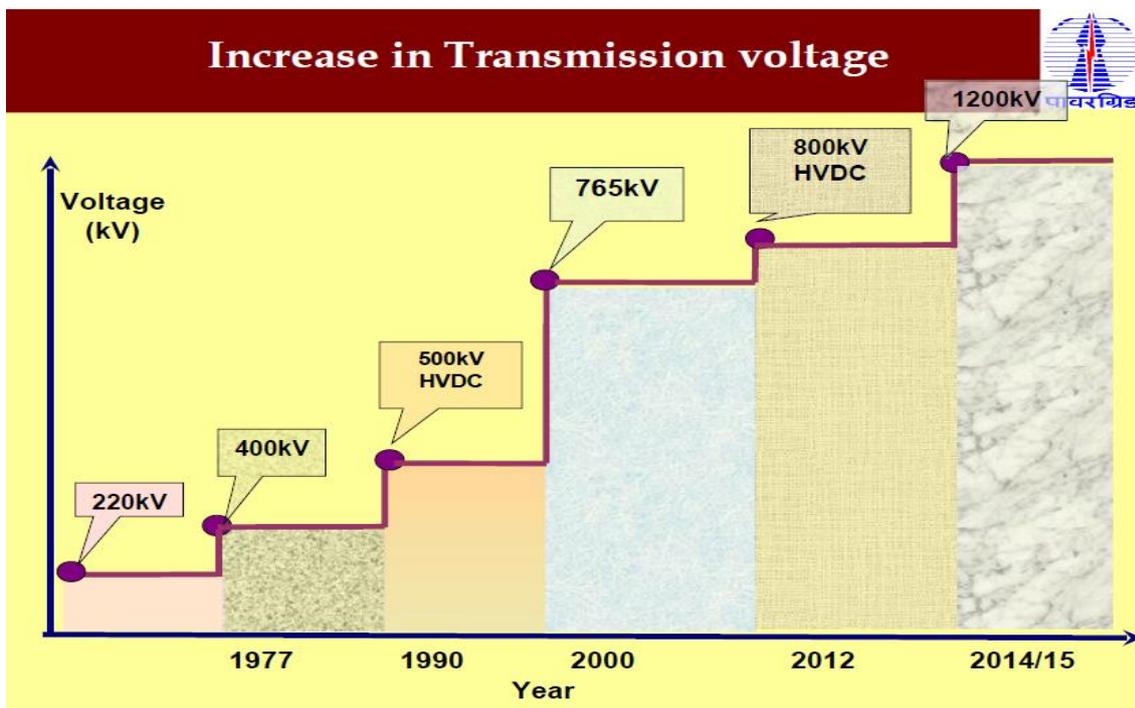
#### **3.1.1. State of technology**

Due to certain key advancements in the energy scenario certain key concepts have evolved for the construction of the overlay grids that can provide the energy transfer corridors:

- 1 Three- Phase AC technology 50 Hz (AC grids) with voltages >400 KV (750 KV,1000 KV)
- 2 Three- Phase AC technology with reduced frequency (AC grids 16 2/3 HZ) with voltages > 400 KV
- 3 HVDC with network controlled converters (LCC-HVDC, HVDC classic)
- 4 HVDC with self-commutated converters (VSC-HVDC)

Constant research into the development of three phase AC technology as a result of an increasing requirement on transmitted power and distance has introduced increased voltage levels.

Overhead lines, cables as well as Gas insulated lines (GIL) are now available as AC transport conductors with a sophisticated technology as well as lower initial investment costs, overhead lines provide a standard solution for high transmission voltages. Line conductor monitoring, high temperature conductors, considerable improvement of towers using less space and field strength distribution are some of the developments in overhead line technology.



**Figure 17: Increase in the deployed transmission voltage levels in India**  
 Source: Power Grid Corporation of India Limited

Reduced frequency Three-Phase systems as an alternative between AC and DC grids was recently introduced for discussions. A reduced frequency of  $16 \frac{2}{3}$  Hz was conceptualized and is now used in certain countries as traction power supply. Larger distances can be bridged due to reduction in the line impedances. Additionally research needs to be done on these systems so as to introduce this high voltage technology. There is some criticism about these technologies as some equipment's, like transformers for reduced frequency AC systems have larger dimensions. A considerable converter expense also needs to be planned which is required with DC grids to convert voltages from AC to DC and vice versa.

The main aim of the introduction of HVDC systems technology was to provide an efficient and a flexible transmission system. Since the supergrid is actually an interconnection between asynchronous grids of a number of countries, HVDC provides the best mode of interconnection. Locally the HVDC converter stations can then be connected to the synchronized AC grids. With the increase in the number and power flow between energy corridors as well as an increasing need of the integration of renewable energy sources into the grid the need for the presence of a transmission system that could provide the required flexibility can be satisfied by the HVDC transmission system. The HVDC system provides the platform to interconnect two AC power systems that are not synchronized as well as transfer of electric power between two distant nodal points through overhead transmission or submarine cables. HVDC systems are more cost effective than AC systems via overhead lines as the costs of transformer stations are not considerable. Long distance HVDC system become economical between 800 and 1200 kilometres provide the critical length. At distances less than this the AC overhead lines are more economical today. HVDC has definite advantages with longer cable connections. For the supergrid deployment, the HVDC transmission system provides superior working conditions, a better power flow control and a definite platform for future additions on the supply side which can be from other conventional generation plants or renewable energy parks. The HVDC systems in parallel with the AC systems provide such a characteristic which can affect the controllability and flexibility of the bulk power system.

The converter stations form the nodes of the working of an HVDC transmission system. Currently two kinds of converter technologies, the Line Commutated Current Source Converters (CSC's) and self-commutated voltage source converters (VSC's) are mostly used in the HVDC transmission systems.

HVDC systems based on the principle of conventional CSC's require a substantially large generation source with a very high level of short circuit ratio in order to operate reliably. In other words there is a need for the transference of reactive power from the AC system at to the inverter to accomplish the conversion process which is nearly 50 percent of the total active power through the converter. Based on the CSC technology principle, power flow direction can be reversed only by reversing the Direct Current DC voltage polarity. This characteristic employs a switching technique in case the CSC system is used for building a Multi Terminal Direct Current (MTDC) System.

In comparison, VSCs utilizing the (IGBT) Insulated Gate bipolar transistor valves as well as pulse width modulation techniques can lead to the production of a near sinusoidal AC voltage which is fully controllable with respect to magnitude and phase of the AC wave. Unlike the CSC systems, VSCs have no reactive power demand and can exchange the reactive power with the AC grid.

VSCs can rapidly control the active power exchange by controlling the phase angle of the produced voltage as well as control the reactive power at each terminal by controlling the magnitude of VSC voltage independent of the Direct Current power transmission. Due to this property, VSCs can be installed anywhere in the AC grid irrespective of the short circuit current capacity. Moreover to change the direction of the power flow in its DC link, VSC does not need to reverse the voltage polarity. This power reversal is observed by changing the direction of the current. Many attempts have already been made to conceptualise the formation of the meshed grids using classic HVDC or CSC technology. However due to the high amount of complexity involved the studies were thereby limited to a maximum of 3 nodes. Expanding the concept the VSC-HVDC provides the option for a multi terminal system which is the basis for the deployment of a supergrid as the number of nodes and the kind of grid topology utilized does not have any limit with regards to VSC-HVDC.

### **3.1.2. VSC-HVDC Functional Principle:**

The working of a VSC converter is based on the synchronous functioning of a 6-pulse bridge circuit of IGBT's (power transistors) controlled by a clocked control signal generating pulses in the range of kilo-hertz frequencies. Provision has to be provided for the serial switching of the multiple semiconductors in order to account for the limited reverse voltage capacity of the power electronic elements. Intelligent control techniques can introduce a high flexibility in the output voltage control in order to obtain the desired active and reactive power.

AC voltage is formed by the use of PWM modulation in case of PWM VSC converters and DC voltage is smoothened by the use of DC capacitors. There is a higher precision of synchronism if a higher clock frequency is used. PWM technology has been in use for nearly a decade now and two and three level VSC converters are now in the market.

Constant research into upgrading the ratings and the frequency of VSC converters has led to the use of a modular construction based on the use of multi-level technology. Sub-modules consisting of half bridges having two valves and a module capacitor are at the heart of sub-module architectures. Partial voltages of the sub-modules combine to the complete voltage of the branches and thereby branches can act as controllable voltage sources.

Using Modular circuits VSC technology coupled with a complicated control process can decrease the operating frequency of the converters and thereby directly affect the losses at the converter station which can amount to about 1 percent. AC voltages are generated by a cumulative process consisting of step functions with hundreds of voltage steps. This directly affects the harmonic components in the voltage sinusoids which are directly reduced and thus improving the overall Total Harmonic Distortion (THD) of the voltage wave. In HVDC technology based on VSC converters reversal of power depends on the reversal of current unlike the LCC HVDC in which reversal of power depends on the reversal of voltage. Polarity of DC voltage thereby always remains the same and hence makes the use of XLPE-DC cables possible.

### **3.1.3. VSC Based Multi Terminal HVDC and its application in the Supergrid Deployment.**

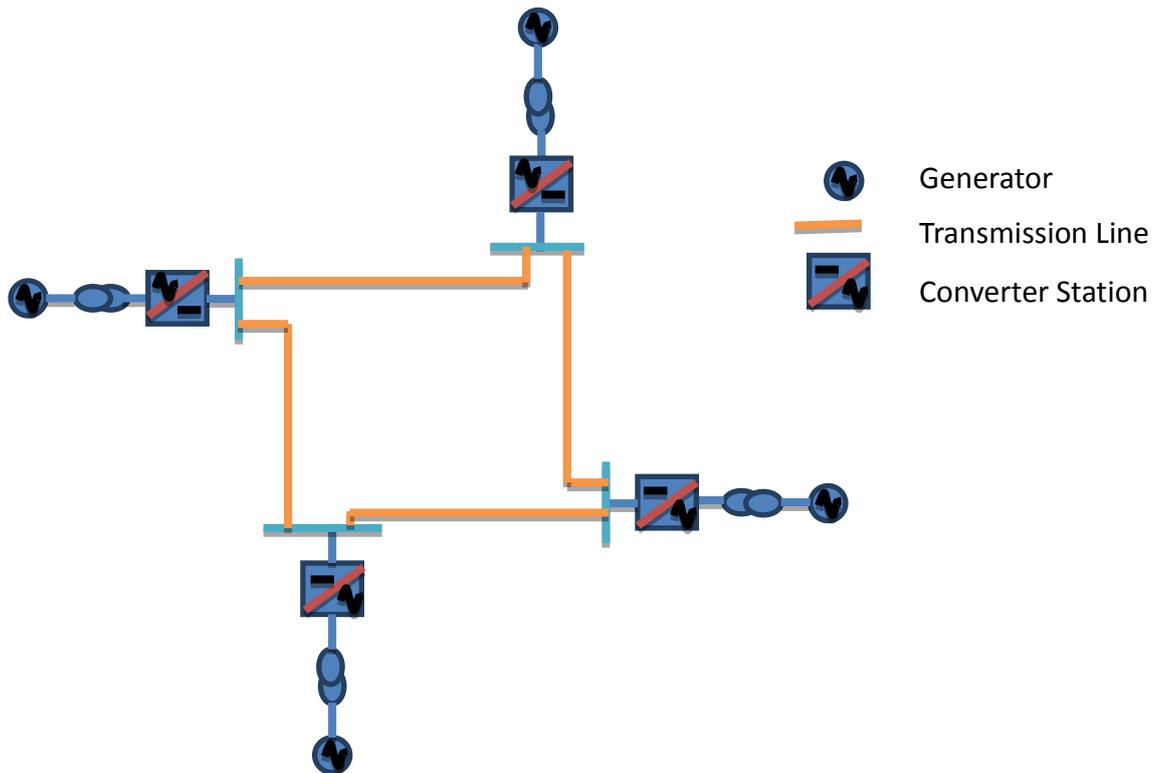
Multi terminal Direct Current systems (MTDC) were first deployed in practical power systems until 1987 when the first MTDC system was introduced by installing a third terminal in Corsica to the already existing link between Sardinia and Italy.

Another landmark achievement was the completion of the first large MTDC system by ABB in 1992 which was again a three terminal HVDC system. While as before, the MTDC systems used to be based on the LCC converters, because of huge advances in the field of VSC converters and their subsequent advantages the shift is gradual towards using the VSC converters for MTDC system deployment. In India itself POWERGRID corporation of India (PGCIL) is installing +/-800 kV, 6000 MW HVDC multi-terminal system of approx length of 1728 km from North Eastern Region to Agra which will consist of one rectifier station in Biswanath Chariali (in North Eastern Region), second one in Alipurduar (in Eastern

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Region) and Inverter station at Agra (in Northern Region). This will be the first multi terminal system in India consisting of VSC converters.

For the deployment of MTDC system two types of configurations are possible - the parallel connection and the series connection. While the parallel connection allows the DC terminals to operate around a single rated voltage VDC, the series connection involves a single converter that controls the current around a common current rating and the rest of the converters control the power. The series connection is more suited for CSC MTDC systems as the CSCs on the DC side provide the same functions of a voltage source and thus can be introduced in series connections without any subsequent need for special switching control. Among other drawbacks of this configuration, the most significant in the HVDC applications is its inability to control the losses and the use of complicated insulation. More importantly if circumstances cause one of the DC lines to be disconnected which may be due to fault conditions; the power flow in the entire DC grid is affected. Hence only parallel configuration is recommended by power engineers to be used in the MTDC systems. Consequently if CSCs are used for the parallel connection of an MTDC system, a complicated and special switching arrangement has to be made to overcome the precise voltage balancing between the converters which arise because of the voltage source nature of the CSCs.



**Figure 18: Parallel connection of DC terminals**  
 [Farhan Beg 2014]

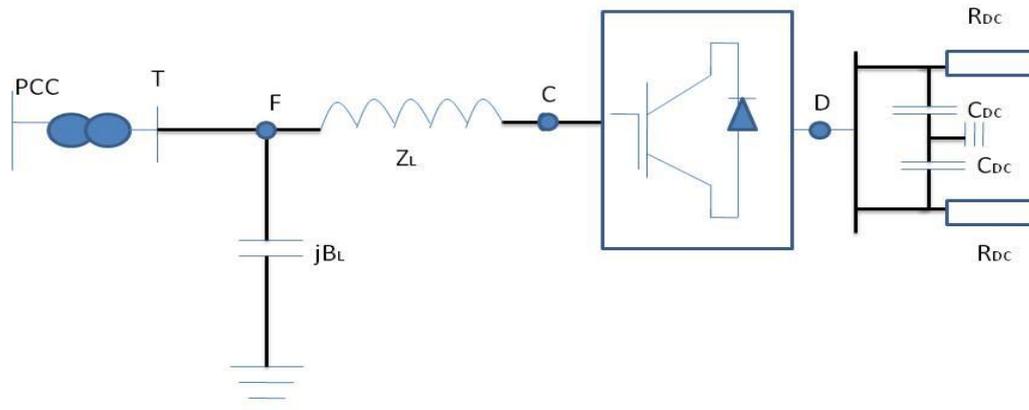
This cumulates into a more serious technical issue if the converter stations are far away which is highly probable in case of supergrid MTDC systems since an inherent need of fast communication channels is needed. The presence of Smart Grids in each of the participating countries can to a large extent mitigate this technical problem with the presence of a very fast and reliable communication highway. Thus formation of more than 5 terminal MTDC system based of CSC converter stations is highly discouraged. On the contrary, if VSCs are used to form a parallel configuration, their functioning as an ideal current do not pose any serious technical difficulties. As already shown, reversal of power in case of VSCs can occur by reversing the direction of current keeping the polarity of the DC voltage unchanged. This capability of the VSCs is suited for the construction of an MTDC system. The construction of a bulk power system such as a supergrid VSC based MTDC system having parallel connected converters has a great potential. The DC supergrid can connect many unsynchronized grids and provide a definite medium to integrate the renewable energy from various distributed resources around the subcontinent. This proposition of a DC supergrid is a direct consequence of the compatibility of VSC converters with a basic parallel

connection of a reliable DC grid integrated into the conventional AC grids. Investigative research has to be conducted to observe the effect of the MTDC systems on a large power system since this proposition is relatively new. The Supergrid for the Indian sub-continent has to be dynamically connected with high flexibility to address the different requirements of the countries taking part in such a project. Not only should the supergrid provide a stable power flow depending upon the demand and supply difference at different times of the year it should also be able to absorb the intermittent and highly variable renewable power from energy sources that are located all over the sub-continent. The renewable energy sources are intermittent by nature and can thus prove to be hazardous to the normal functioning of a large inter connected grid that requires system stability. The DC supergrid based on the VSC converter systems can allow non-conventional energy from different renewable energy sources to feed electric power into the common DC supergrid thereby providing all the participant countries a steady access to a reliable and stable source of electricity generation.

#### **3.1.4. VSC HVDC station Modelling**

The need to understand the underlying structure of the VSC station model arises because of the presence of several VSC stations in the VSC based MTDC systems. The following figure shows the elements constituting a VSC station. The model consists of AC buses, series reactance, AC filters, coupling transformers and converter blocks on the AC side and consists of the DC bus, the DC filter and the DC line on the DC side. A single line represents the DC side of the model.

The point of common connection acts as a medium from where the VSC station is connected to the AC grid. The Point of common connection (PCC) is connected to the AC side of the VSC through a converter transformer, shunt filter and a phase reactor while as on the other side the DC bus, at which a shunt DC capacitor is connected to the ground, is connected to the DC line on one side and the VSC on the other side.



**Figure 19: Modelling of VSC HVDC stations**

Source: Author

### 3.2. Power Flow Analysis

For the power flow analysis of the supergrid, an assumption has been made that the topology deployed consists of a meshed grid. Different methods and calculation algorithms have been proposed for the power flow or load flow analysis of three-phase AC systems and thereby refined with increasing complexity of the various attributes. The power flow analysis of DC meshed grid depicts a much simplified and exceptional case of the AC power flow analysis. In case of DC power systems, for stationary conditions the reactive power and the reactive network devices are non-existent because of the inherent zero frequency operation of the DC and hence the voltage can be influenced by the active power flow. Quality of power supply is thus a function of voltage and thereby only voltage active power control is observed as a control system for DC grids.

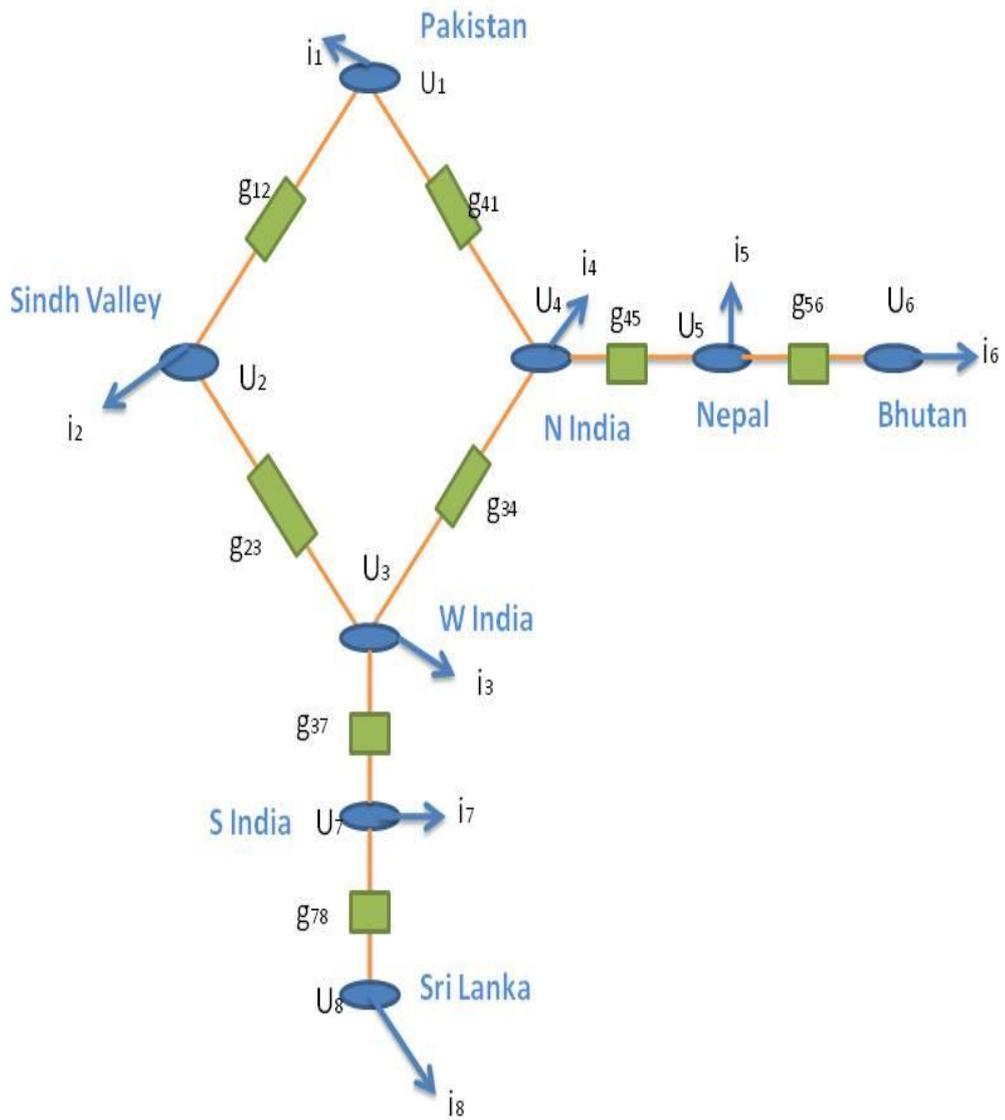
The most common practical analysis methods for power flow consist of the Newton Raphson method and the method of joints. The method of joints is based on the principle of current balance and is solved iteratively using the Gaus-Seidel method to obtain the required parameters. The Newton Raphson method uses the power balance techniques of the nodes. Certain enhancements are done in order to improve the convergency and increase the speed of algorithmic calculations.

Calculation algorithms have been adapted for the use in the VSC HVDC system that is a sub-module of the supergrid.

### **3.2.1. Power flow analysis methods adaption for DC grids:**

Mathematical calculation with a relatively less complexity is observed when the power flow methods were applied to the DC systems than in the three-phase systems because of the crossing over of the complex calculations in the real domain. Consequently the admittance matrix  $[Y]$  of the grid converts to the conductance matrix  $[G]$ . However the normal step by step process consisting of the creation of the system of equations followed by the analysis of network and the direction arrows depicting the direction of flow of power is determined.

For the calculation of the conductance matrix, Kirchhoff's Voltage law is applied at various nodes, i.e. various node equations are formed and the product of conductance and voltage difference replaces the branch currents.



**Figure 20: Analysis and Definition of quantities and arrows in a network**  
 [Farhan Beg 2014]

$$I_1 = -I_{12} - I_{14} = -\frac{U_1 - U_2}{g_{12}} - \frac{U_1 - U_4}{g_{14}}$$

$$I_2 = I_{12} - I_{23} = \frac{U_1 - U_2}{g_{12}} - \frac{U_2 - U_3}{g_{23}}$$

$$I_3 = I_{23} - I_{34} - I_{37} = U_2 - \frac{U_3}{g_{23}} - (U_3 - U_4)g_{34} - \frac{U_3 - U_7}{g_{37}}$$

$$I_4 = -I_{14} + I_{34} - I_{45} = -\frac{U_4 - U_1}{g_{14}} + \frac{U_3 - U_4}{g_{34}} - \frac{U_4 - U_5}{g_{45}}$$

$$I_5 = I_{45} - I_{56} = U_4 - \frac{U_5}{g_{45}} - (U_5 - U_6/g_{56})$$

$$I_6 = I_{56} = U_5 - \frac{U_6}{g_{56}}$$

$$I_7 = I_{37} - I_{78} = U_3 - \frac{U_7}{g_{37}} - U_7 - \frac{U_8}{g_{78}}$$

$$I_8 = U_7 - \frac{U_8}{g_{78}}$$

The conductance matrix is arranged after the formation of the network equations and replacing the branch currents by the product of conductance and the node voltage difference. In the complete analysis efforts have always been made to replace the current by its equivalent quantities depending on the network state. In the conduction matrix, since the serial voltages are known keeping in mind that the node voltage and the serial voltages occur in equal measure, a separation is necessary. Thereby the general notation is.

$$[G]. [U] + [GZ]. [UZ] = [I]$$

The Gaus Seidel method is the most common iterative method that is used to solve the system of linear equation as it involves the least complexity. Another possibility consists of using the Jacobian method based on the node equations. For solving the equations of the grid based on various bus voltages which are chosen based on the known and unknown values there is a definite need to choose a slack bus which acts as a reference bus and is often the bus consisting of the largest generation capacity. The system of equations is thus modified with the provided slack voltage  $U_{sl}$ .

$$[U]V = [G]V - 1. \{[I]V - [GZ]V - [UZ] - USL. [G]r\}$$

Using the iterative solution in every step, node currents are first determined using the node power and then the new state vector is defined which is calculated for the node voltage.

$$[diag[U]V]^T * [Po]V = [I]z$$

The power flow, slack power and the power loss can be determined after converging the voltages or node power with the abort criterion after the required convergency is obtained which in most cases is reached after a maximum of ten steps.

It is of course an inherent characteristic of applying power flow analysis to DC systems that the PV nodes that are analogous to the three-phase system don't exist in the DC systems. This is attributed to the fact that only power or voltage is possible on each node as only a single degree of freedom exists.

The modification of the Newton Raphson method for application to the DC grids is also possible. This process involves very high complexity and thus this method can be done with at most 4 steps to obtain the same accuracy. Newtonian directional null method lies at the heart of the Newton Raphson method. Using the Taylor series expansion the node power balance is linearized and thereby resolved in each iteration step which leads to the formation of a Jacobian matrix [J].

### Linearized equation:

$$\begin{bmatrix} [\Delta P] \\ [\Delta Q] \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} * \begin{bmatrix} [\Delta \vartheta] \\ [\Delta U] \end{bmatrix} = [J] * \begin{bmatrix} [\Delta \vartheta] \\ [\Delta U] \end{bmatrix}$$

And since in DC systems  $\Delta Q = 0$  and  $\Delta \vartheta = 0$ ;

$$[\Delta P] = [N] * [\Delta U]$$

and the simplified Jacobian matrix consists of,

$$[N] = \begin{bmatrix} \partial P1/\partial U1 & \partial P1/\partial U2 & \partial P1/\partial U3 & \dots & \partial P1/\partial Un \\ \partial P2/\partial U1 & \partial P2/\partial U2 & \partial P2/\partial U3 & \dots & \partial P2/\partial Un \\ \partial P3/\partial U1 & \partial P3/\partial U2 & \partial P3/\partial U3 & \dots & \partial P3/\partial Un \\ \partial P4/\partial U1 & \partial P4/\partial U2 & \partial P4/\partial U3 & \dots & \partial P4/\partial Un \\ \dots & \dots & \dots & \ddots & \dots \\ \partial Pn/\partial U1 & \partial Pn/\partial U2 & \partial Pn/\partial U3 & \dots & \partial Pn/\partial Un \end{bmatrix}$$

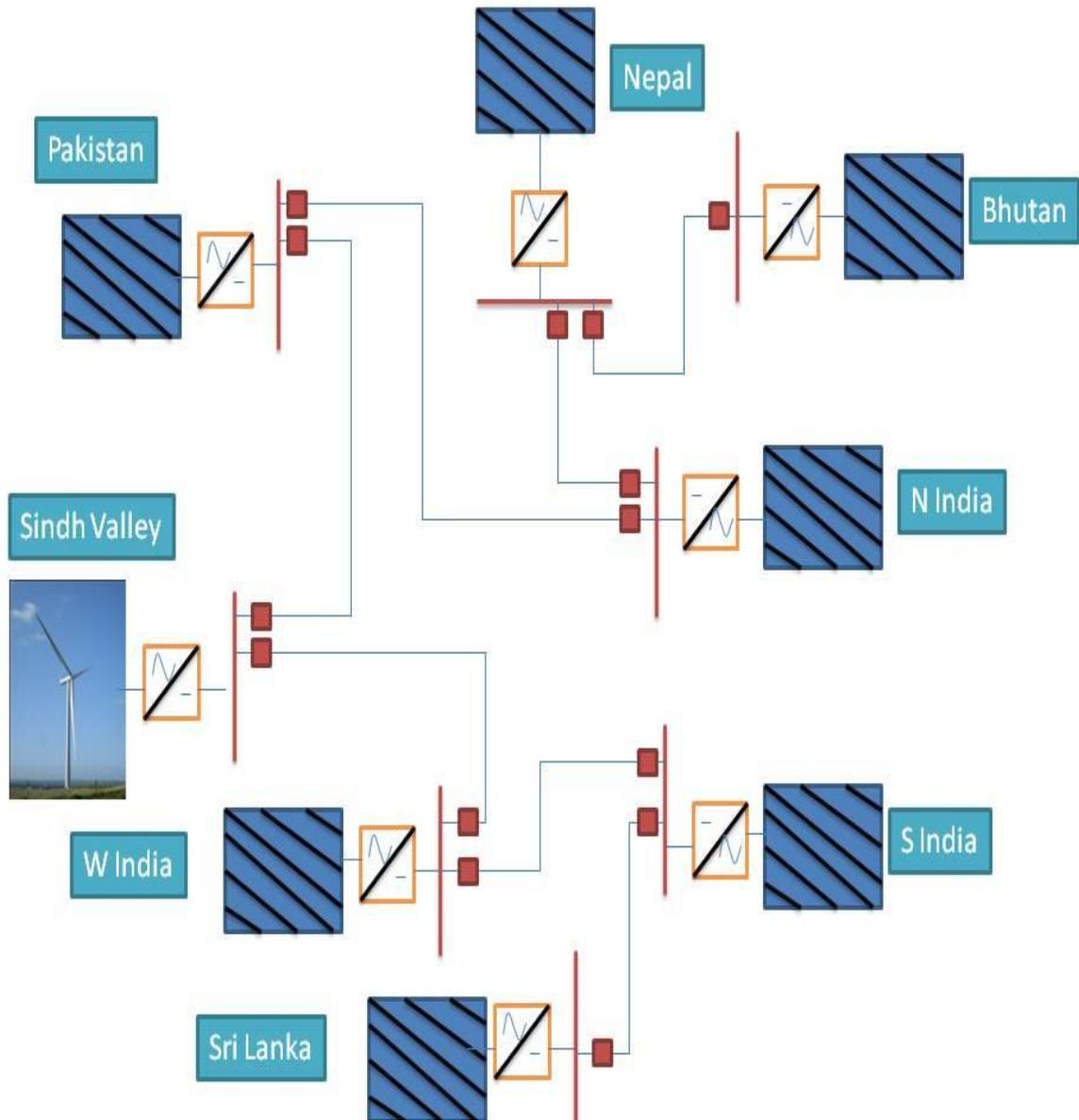
Accordingly,

$$[\Delta U] = [N]^{-1} * [\Delta P]$$

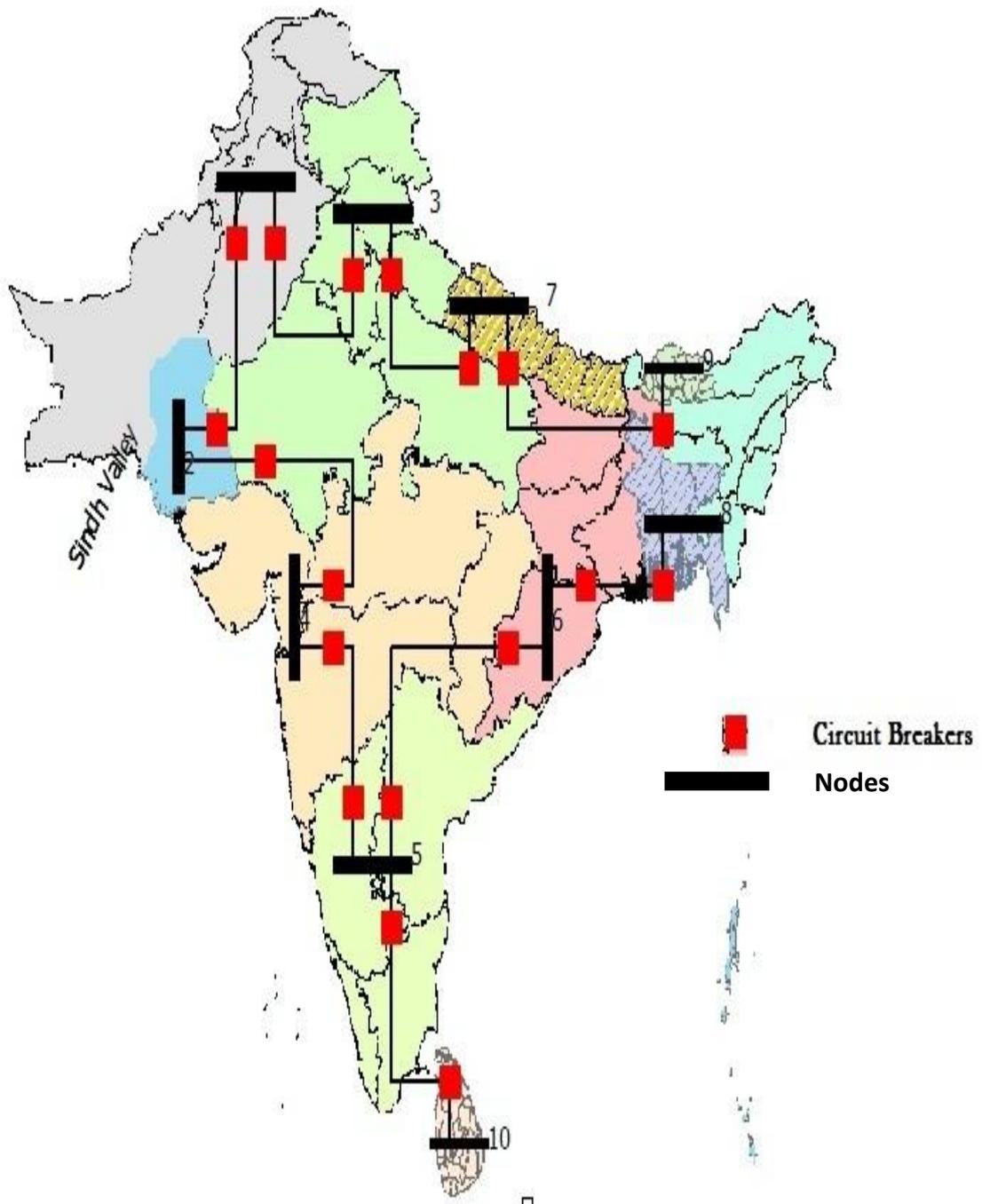
With

$$[\Delta P] = \text{diag}[U] * [G]V * [U]V - [P0]$$

The state vector of voltages are corrected iteratively until the required convergence is achieved which occurs after a maximum of 5 iteration loops.



**Figure 21: Draft of DC multi terminal grid**  
[Farhan Beg 2014]



**Figure 22: Indian subcontinent Draft grid**  
 [Farhan Beg 2014]

### **3.3. Risk Assessment**

It has already been mentioned before that the key hurdles in the supergrid deployment stand to be non-technical. Several key factors need to be analysed for an efficient delivery of the supergrid. In the following discussion a brief risk assessment has been conducted to assess, evaluate, rank and map the key issues that are highly probable to retard the development of the supergrid in the Indian subcontinent. The basic reason to undergo a risk assessment is to stimulate a wider and a progressive discussion, and offer a highly effective visual narrative that can lead to important steps necessary for a successful deployment of the supergrid.

To conceptualise the idea of a reliable and a secure source of electricity that has an adaptive and a need-based element to it, the Indian subcontinent is left with a highly feasible option of linking the transmission networks of all the ASEAN countries and thereby integrating the renewable energy through optimal design and innovation into the supergrid. The Indian subcontinent consists of a diverse economic and cultural heritage as well as a highly unstable political sphere. The idea of linking the electricity grids through high voltage energy corridors utilizing the VSC HVDC systems and other inter connectors integrate the alternating current (AC) grid network of the member countries, requires a conducive analysis at every step of the supergrid deployment.

An assessment consisting of an extensive literary review was conducted on the inter connection of grids in the Indian subcontinent and the following high risk parameters were identified:

- Political
- Technical
- Infrastructural
- Social
- Financial

Consequently a risk map was formed for the high risk items which also reflects a similar risk map that was formed for the European supergrid deployment. It constituted of identification of main risk items in each sub category and a risk identification process to highlight the key risks facing the development of the supergrid.

The rating of the risk components was done on their probability of occurrence or their current state on a scale of 1 to 10. Weighing factors are then applied on the basis of potential effects of the risk item on a 1-5 scale. Finally the risk percentage is derived using the formula:

$$FR = ((\sum WF * RR)) / \sum (WF + 10) * 100;$$

Where WF= Weighing factor

RR = Risk Rating

FR= Final Risk Percentage

The success of the supergrid deployment must sort out the non-technical issues taking into account the turbulent state of political instability in the Indian subcontinent as well as other infrastructural loopholes. Moreover the supergrid spans over a large area encompassing 7 member countries and thus harmonization and coordination of regulatory policies on a large scale is an important factor.

### **3.3.1. Risks, Risk ratings and Recommendations**

A) Policy Risk:

- The electricity framework in the subcontinent is highly monolithic that is tightly regulated and dominated by the central governments and public sector utilities.
- Certain energy corridors are already in place for the import and export of electricity between member countries such as India to Sri Lanka and India to Bhutan but there is a need of interconnecting all the countries into a common framework. The Indian subcontinent is far from a competitive electricity market.
- Many of the member countries offer subsidies for the Renewable Energy endeavours buoyed by a large financial package but the harmonisation of support mechanisms is not deployed yet.
- There has to be a symmetrical development across the member countries, which is only possible by policy harmonisation in order to provide certainty to private investors.

		Risk Consequence Weightings		Weighted Score Calculation		
	Risk Area	Weighting Factor	Percentage value	Risk Rating	Weighted Score	Weighted percentage score
	A) Policy	18	100%		158/180	
A1)	Regulatory Uncertainty	5	28	9	45	<b>87.8%</b>
A2)	Development towards a single electricity market	4	22	9	36	
A3)	Coordination and harmonisation of RE support	4	22	8	32	
A4)	Facilitating growth of investment policies to boost increase interconnection of transmission	5	28	9	45	

**Figure 23: Risk percentage calculation for Risk Area= Policy**  
[Farhan Beg 2014]

#### B) Political

- Even though it is very difficult to assign ranks to the political risk or have a probabilistic analysis of it, it becomes very crucial to work through the minute details of such a factor because political instability can have a substantial impact on the decision making.
- The subcontinent's current political culture, which is entirely based on fragmented political tendencies and multi coalition governments, make transforming India subcontinent's energy culture into a functioning dynamic system difficult.
- Certain key reforms in the energy sphere that can considerably impact the energy scenario are pending and waiting for approval due to political impasse. This results in the build-up of socio-political tensions and thus leads to a negative growth of the economy.
- Politicians have half-heartedly always supported the decarbonisation of the electricity framework even though they stand up in arms against the debts and economic

meltdowns. However the politicians always debate against the developed countries in terms of clean energy by stating the most of the carbon footprint is produced by the developed countries and the countries in the Indian subcontinent have to follow the same process in order to become developed.

- Steady tensions between the member countries can hamper the deployment of the supergrid. The Indian Subcontinent has a history of tense relations with its neighbours but once deployed the supergrid can create a flexible and interconnected network that is secure against geopolitical disruption. An integrated grid provides access to a variety of renewable technologies as well as access to conventional thermal technologies and significant pumped storage reserves. For these reasons it should serve to protect the Indian subcontinent against systemic macroeconomic risks, particularly with regard to fossil fuel price shocks.
- A very important rationale of the Supergrid is that it benefits the subcontinent as a whole and not every member country equally. Thereby there will always be a fair amount of horse-trading between the member countries. Countries that are rich in natural resources could observe the wholesale energy prices to rise dramatically. The reason behind it is that countries with an excess of generation, such as Bhutan and Sri Lanka with abundant hydro reserves will be able to access higher prices from other member States for the same amount of electric power. It can affect the socioeconomic culture as asking the consumer to pay extra because of interconnection doesn't seem to be a wise thing. "Fuel poverty" is an increasingly hot topic at a political level. Countries such as Pakistan and India have an abundance of low cost coal, though they both need to technologically advance the coal refining processes to increase efficient production. There is no need to stress their societies and buy electricity from other member countries to their economic detriment.

	Risk Area	Risk Consequence Weightings		Weighted Score Calculation		
		Weighting Factor	Percentage value	Risk Rating	Weighted Score	Weighted percentage score
	Political	16	100%		122/160	
B1)	Political intervention in power market	5	31	10	50	<b>76.3%</b>
B2)	Geopolitical risk	3	15	4	12	
B3)	Political tensions between member states	4	25	8	32	
B4)	Collaborative negotiations	4	25	7	28	

**Figure 24: Risk percentage calculation for Risk Area= Political**  
[Farhan Beg 2014]

### . C) Financial Risk

- The private investments in the power sector are far below the expectations and need to be increased substantially. Considerable concerns remain about the regional concentration of private investments in a few member countries. In India private investments have started pouring in and increased steadily after the liberalisation of oil, gas and power sectors. However in spite of all these investments and the subsequent positive changes that private investment brought in this sector, the achievement remains a half success.
- Countries in the Indian subcontinent need a considerable amount of private investment to build a reliable and an adequate energy chain.
- A considerable lack of depth in financial investment results in hampering of the delivery and deployment of such a magnanimous project.
- Lack of depth in the financial sector coupled with high interest rates makes accessing the debt capital very difficult, even more so when long term infra-structure development projects in many countries are backed by PPA's (power purchase agreements) inclusive of strong cash flows and balance sheets.

	Risk Area	Risk Consequence Weightings		Weighted Score Calculation		
		Weighting Factor	Percentage value	Risk Rating	Weighing Score	Weighted percentage score
	Financial	18	100%		154/180	
C1)	Regional Concentration of private investments	5	28	10	50	<b>85.6%</b>
C2)	Investment flow for building a reliable energy chain	5	28	8	40	
C3)	Lack of depth in the financial delivery chain	4	22	8	32	
C4)	Debt capital access	4	22	8	32	

**Figure 25: Risk percentage calculation for Risk Area= Financial**  
[Farhan Beg 2014]

D) Infrastructural risks:

- The supergrid will need effective communication platforms for the easy flow of information from one part of the subcontinent to another. This can be made possible only through a dynamic communication protocol made possible only by the presence of a smart grid in each of the member states. The Smart Grid provides the basic framework required for the establishing of an interconnected network of grids. Thus a supergrid is actually an interconnection of many Smart Grids.
- Member countries in the subcontinent aren't yet to the stage where their traditional grid can be called Smart. This can be attributed to many reasons but there is a general perception that the planned interconnection of grids can lead to the establishment of a large networked grid which can in turn lead to mitigation of the supply demand gap

Thereby the member countries in a bid to advance their power transferring capabilities will go ahead with upgrading the system

- The supply chain capacity will have to be flexed in indefinite proportions in the subcontinent in order to provide the required infra-structure for an inter-connected grid.
- The plan to integrate the RES in the subcontinent and the storage reserves has to be focussed on market integration. A well planned strategic infrastructure will lower the risks to stake holders by providing a reliable market for the RES.

		Risk Consequence Weightings		Weighted Score Calculation		
	Risk Area	Weighting Factor	Percentage value	Risk Rating	Weighting Score	Weighted percentage score
	Infrastructural	15	100%		96/150	
D1)	Supply chain capacity	5	33	9	45	<b>66%</b>
D2)	Stranded assets	3	20	4	9	
D3)	Common Communication policy establishment	4	27	6	24	
D4)	Development phasing	3	20	6	18	

**Figure 26: Risk percentage calculation for Risk Area= Infra-structural**  
[Farhan Beg 2014]

## E) Technical Risk:

- Numerous projects involving high voltage transmission, both onshore and subsea are in operation. Recent examples include the subsea BritNED interconnector between England and the Netherlands (250km, 1000MW subsea HVDC connection) and the world's longest onshore HVDC link, the 2500km Rio Madeira link, from Porto Vehlo to Sao Paolo. Globally, over 5000km of HVDC subsea cables are in operation.
- Electricity demand will continue to rise unabated. In the development of the Supergrid, technical selection of generation will play a key role in decarbonising Europe to 2050. Policy and political measures deeply affect this. The nuclear phase out post Fukushima will result in a steady reduction of nuclear output. If this continues, a replacement to reduce GHG emissions is required.
- ABB and ALSTOM have recently declared that production of HVDC circuit breakers, a device that has been a hurdle for the deployment of HVDC projects until now. With these circuit breakers, interconnection of HVDC lines to form the basic infrastructure for the supergrid is now possible.
- The number of renewable systems that will be connected to the supergrid will be increasing and thus the energy produced can potentially supersede the net demand. Rather than wasting the excess power, the generated energy is diverted to storage systems. Pumped hydro storage is a very common storage technique worldwide.

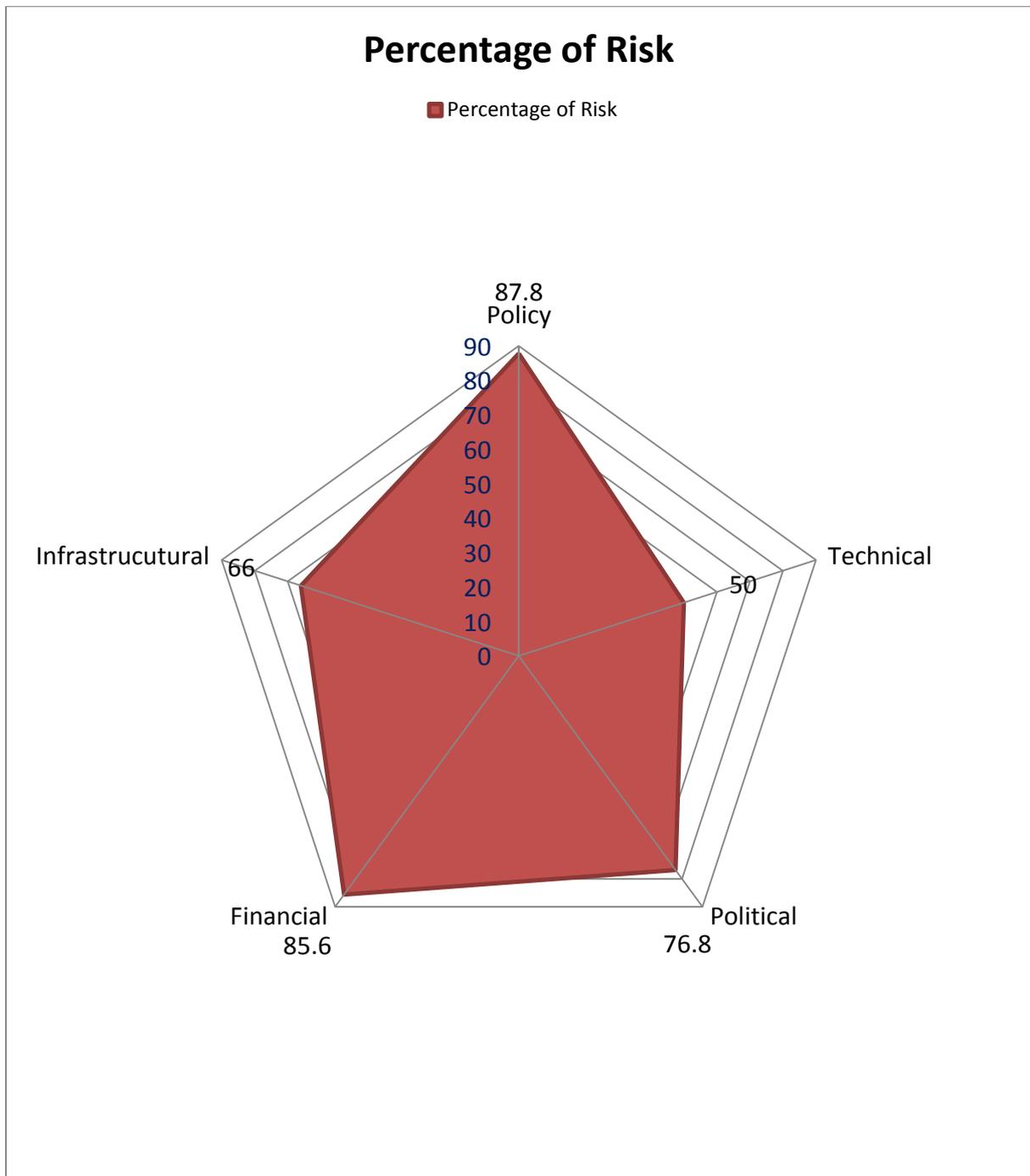
	Technical	Risk Consequence Weightings		Weighted Score Calculation		
		Weighting Factor	Percentage value	Risk Rating	Weighing Score	Weighted percentage score
E1)	Technical Complexity	2	17	3	6	<b>50%</b>
E2)	Technical Selection on path to decarbonisation	4	33	6	24	
E3)	Storage	3	25	6	18	
E4)	Energy management	3	25	4	12	

**Figure 27: Risk percentage calculation for Risk Area= Technical**

Source: Author

At the onset of the subcontinents decarbonisation agenda as well as the proposal of reliable and clean electricity for all by the end of the next decade, the supergrid can provide the basic platform because of its potential to transcend national barriers and absorb the energy from the RES. However the risk map analysis clearly warns of the upcoming challenges and suggests a planned approach, involving multiple mitigation strategies for the effective implementation of the supergrid.

Urgent action is needed in the key risk areas as identified by the risk map analysis. It should of course be noted that the main job of the risk map analysis as conducted in this research was to provide a strong visual narrative in order to stimulate a wider progressive discussion.



**Figure 28: Risk Map for the supergrid deployment in the Indian subcontinent**  
 [Farhan Beg 2014]

## **4. Conclusion:**

The power grids of the future need to be highly adaptive with regards to satisfying the needs of the high growth economies of the future as well as dynamic to balance and effectively transfer the huge quanta of power flow. This flexibility in the grid has been proposed to be achieved by interconnecting several grids in order to form a one nation supergrid spanning borders. Interconnection of the grid provides a platform for a need based power flow backed by generation in areas of high potential and consequent transfer where it can be used most effectively. This networked system is supplemented with a number of decentralised structures that play a part in load coverage as well as allocating excessive energy for power flow.

This paper proposed that a networked topology for supergrid deployment is the most feasible because of its dynamic characteristics to efficiently deal with power flow. This structure was then analysed through load flow methods adapted for DC grids. This practice thereby leads to an interconnection of transmission networks of various participating countries in the subcontinent and also proposed wind power integration from the Sindh valet located in the Southern Pakistan. The paper concluded with a risk assessment which categorically pointed out the various risk factors that can impede the deployment and development of the supergrid. The risk assessment leads to the formulation of a risk map that provides a strong narrative description of the various risk factors.

The supergrid in the Indian subcontinent will be challenging to deploy and certainly require several decades to complete. Yet the benefits accrued by each nation make the investment worthwhile to a billion people seeking clean, reliable electricity

## 5. References:

- 1: Van Hertem, Dirk, and Mehrdad Ghandhari. "Multi-terminal VSC HVDC for the European supergrid: Obstacles." *Renewable and sustainable energy reviews* 14.9 (2010): 3156-3163.
- 2: Kumar, Akhil. "An efficient SuperGrid protocol for high availability and load balancing." *Computers, IEEE Transactions on* 49.10 (2000): 1126-1133.
- 3: Gordon, Stephanie. "Supergrid to the rescue [electricity supply security]." *Power Engineer* 20.5 (2006): 30-33.
- 4: Van Hertem, Dirk, Mehrdad Ghandhari, and Marko Delimar. "Technical limitations towards a SuperGrid—A European prospective." *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International*. IEEE, 2010.
- 5: MaCilwain, Colin. "Supergrid." *Nature* 468.7324 (2010): 624-625.
- 6: Vrana, T. K., et al. "The North Sea supergrid-a technical perspective." *AC and DC Power Transmission, 2010. ACDC. 9th IET International Conference on*. IET, 2010.
- 7: Vrana, Til Kristian, and Olav Bjarte Fosso. "Technical aspects of the north sea Supergrid." *CIGRE Electra, November* (2011).
- 8: Overbye, Thomas J., et al. "National Energy Supergrid Workshop Report." *Crowne Plaza Cabana Palo Alto Hotel, Palo Alto, California* (2002).
- 9: Dike, D. O., and O. D. Momoh. "An Integrated AC/DC Super-Grid System-A Mechanism to Solving the North American Power Crisis." *System Theory, 2007. SSST'07. Thirty-Ninth Southeastern Symposium on*. IEEE, 2007.
- 10: Jha, Alok. "Sun, Wind and Wave-powered: Europe Unites to Build Renewable Energy 'Supergrid'." *The Guardian* 3 (2010).
- 11: Jackson, R. L., et al. "The condition of the supergrid and a strategy for refurbishment." *Proc. IEE Conf. 'Revitalising Transmission and Distribution Systems', London, 25-27 February 1987*. 1987.
- 12: Grant, Paul M. "The energy supergrid." *Proceedings World Energy Conference*. 2004.
- 13: Wald, Matthew L. "How to build the supergrid." *Scientific American* 303.5 (2010): 56-61
- 14: Feltes, J. W., B. D. Gemmell, and D. Retzmann. "From smart grid to supergrid: Solutions with HVDC and FACTS for grid access of renewable energy sources." *Power and Energy Society General Meeting, 2011 IEEE*. IEEE, 2011.
- 15: Ghosh, Sajal. "Electricity consumption and economic growth in India." *Energy policy* 30.2 (2002): 125-129.
- 16: Bose, Ranjan Kumar, and Megha Shukla. "Elasticities of electricity demand in India." *Energy Policy* 27.3 (1999): 137-146.
- 17: Joseph, Kelli L. "The politics of power: Electricity reform in India." *Energy Policy* 38.1 (2010): 503-511.
- 18: Da Silva, Rodrigo, Remus Teodorescu, and Pedro Rodriguez. "Multilink DC transmission system for supergrid future concepts and wind power integration." *Renewable Power Generation (RPG 2011), IET Conference on*. IET, 2011.
- 19: Topology and control of overlay grids using DC transmission -Final Report - English Version Report of Steinbeis GmbH & Co. KG für Technologietransfer, Stuttgart Represented by PROF. DR. HARALD WEBER Head of Steinbeis Transfer Center FOR APPLIED

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