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Energy transition in megacities towards 100% renewable energy: A case for Delhi

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A B S T R A C T

The transition away from fossil fuels towards renewable energy is critical in preventing perilous climate change, and cities around the world have a significant role in enabling this transition. Cities are innately centres of human, economic and intellectual capital, also contributing to the growing energy demand around the world. This research is a first of its kind to explore the technical feasibility and economic viability of 100% renewable energy systems including power, heat, transport and desalination sectors for a global megacity like Delhi within the North Indian grid region. It presents a technology-rich, multi-sectoral, multi-regional and cost-optimal energy transition pathway for Delhi, which is a hub within the regional energy system. The results of this research indicate that a megacity such as Delhi can benefit and drive a regional energy transition, with reduction in primary energy of over 40%, reduction in energy costs by over 25%, reduction in greenhouse gas emissions, air pollution and associated health costs. While creating more than three times the number of direct energy jobs as of today across North India and Delhi. With the case of Delhi within the North Indian grid, this research provides snapshots of the current and future energy landscapes and discusses several aspects of an energy transition pathway that could lead to an affordable, efficient, sustainable and secure energy future for megacities around the world.

1. Introduction

Global greenhouse gas (GHG) emissions must be reduced by an additional 25% along with existing commitments for 2030, to get on track towards the 1.5 °C temperature goal of the Paris Agreement [1]. In order to enable this, cities around the world have a key role in shaping energy transitions. The city, one of the world's biggest phenomena of the 21st century has evolved greatly over the centuries, particularly in terms of its size, form, structure and composition, while largely maintaining its importance in local, regional and increasingly in global development [2]. However, the definition of a city varies around the world and the United Nations (UN) formulated a consensus that a city can be conceptualised in terms of its urban extent or the degree of urbanisation [2]. This classifies a high-density cluster or urban center as having a density of at least 1500 inhabitants per km^2 and a minimum population of 50,000 [2]. The city as a unit of analysis is critical to overcoming future challenges and for better positioning of cities as engines of sustainable development.

Cities contribute massively to the growing energy demand with two-thirds of global energy consumption, and by extension are responsible for 70% of global GHG emissions [3]. Moreover, cities around the world are home to 55% of the global population, which is expected to increase to nearly two-thirds by 2050 [4]. This implies cities will be central to drive energy transitions in regions and countries around the world. Some cities are making progress, as reported by Carbon Disclosure Project (CDP) that 148 cities had reported a 1.5 °C aligned target by the end of 2020 [5]. While most of these targets were reported by North American and European cities along with a few others, a majority of cities and particularly megacities around the world are yet to devise long-term climate targets [6]. According to the UN [3], urban agglomerations having over 10 million inhabitants are counted as megacities. When it comes to cutting emissions, megacities around the world will have to lead with science-based climate targets including energy pathways for reducing GHG emissions to net zero by 2050 [7,8]. Most of these megacities are from developing regions, with a majority in China and India. In addition, India is set to have seven megacities by 2030 with Delhi set to be the most populous city in the world with over 37 million by 2028, overtaking Tokyo [4].

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India is one of the countries that have been aggressively pursuing renewable energy to drive its economic growth and mitigate climate change [9–11]. However, the Indian economy is still heavily reliant on fossil fuels for energy with the power sector dominated by coal-based electricity generation and the transport sector largely fuelled by imported fossil oil [10,11]. This addiction to fossil fuels has adversely impacted the country not just economically but also environmentally. India is amongst the most water stressed countries and ranks 13th for overall water stress, which is exacerbated by thermal power plants [12]. Northern India, which includes the country's capital city New Delhi and with over 30% of the Indian population, has been experiencing toxic levels of air pollution causing a health emergency across the region in recent times [13], as is the climate energy conundrum across megacities of the world [14]. Despite vast research exploring cities and climate change [8], there are few attempts at exploring comprehensive energy transition pathways for cities embedded in the corresponding regions and nations [15], which entails further research across cities and particularly megacities of the world. This research explores an energy system transition pathway across North India with Delhi towards 100% renewables by 2050. It analyses the development of the energy system (power, heat, transport and desalination sectors) in a Best Policy Scenario (BPS), in which GHG emissions reach zero by 2050 with the comprehensive adoption of sustainable technologies. While there have been studies that have explored transitions of urban energy systems for megacities such as Cairo [16], Istanbul [17–19], Cape Town [18], Shanghai [19] and Beijing [20], along with cities such as Vancouver [21], Oslo [22] and Helsinki, the level of detail is limited. An important aspect in globalised urban energy systems is the regionalisation of energy flows [23], as cities are limited in space and rely on external energy inflows. In this context, an energy transition pathway for a megacity within its surrounding region towards 100% renewables covering all energy demand (from the power, heat, transport and desalination sectors) by 2050 could be an exemplar for other megacities, particularly in the developing regions of the world.

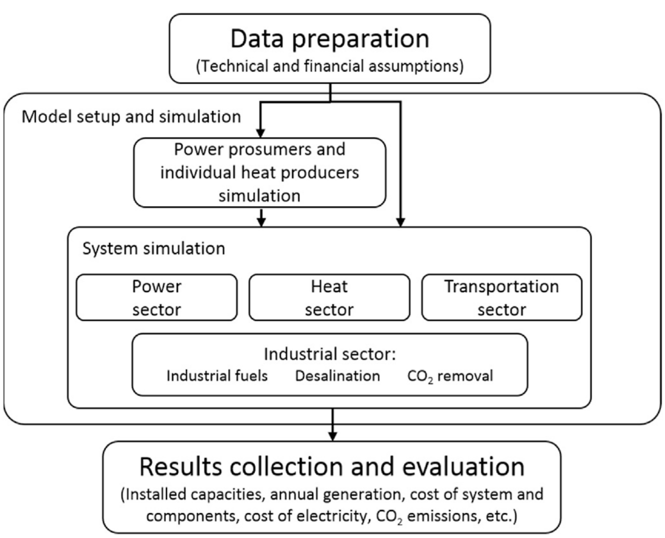

Fig. 1. Process representation of the LUT Energy System Transition Model [24].

2. Methods

The LUT Energy System Transition Model [24–26] involves collating all relevant energy data across power, heat, transport and desalination sectors (Fig. 1), wherein energy demand for industry and industrial process heat is included and part of the power and heat sector but non-energetic demand for chemicals is not included in this research. The data is further structured into eight regions that form the North Indian grid, which are Jammu and Kashmir (including Ladakh), Himachal Pradesh, Punjab and Chandigarh, Uttarakhand, Haryana, Delhi, Rajasthan and Uttar Pradesh (refer to Fig. 2). This is further processed into the model for cost optimal simulations, which occur in two stages. First, a prosumer optimisation on the basis of annual energy cost savings in relation to local retail energy costs is conducted to determine the least cost energy options for prosumers across the eight regions. Prosumers are both consumers and producers of electricity, mainly through rooftop solar PV across residential, commercial and industrial settings, which includes battery storage. They interact with the grid by infusing excess electricity generation, while also contributing to reducing demand [27]. Individual heat producers are those that install heat pumps to meet heat demand across residential, commercial and industrial settings. The next stage involves an overall energy system simulation across the different sectors, wherein the power, heat, transport and desalination sectors are integrated, for the eight regions to derive cost optimal sector-coupled energy mixes for the years 2020–2050. As the eight regions are covered by the North Indian power grid and are connected by transmission lines as indicated in Fig. 2, the resulting cost optimal energy mix is derived from optimal usage of renewable resources across the entire region with imports and exports of electricity in each region, but also benefitting from sector coupling related efficiency gains [26]. Lastly, a post processing of the results involving analyses and visualisation for the North Indian energy system and Delhi are carried out. Refer to the Supplementary Material for more details

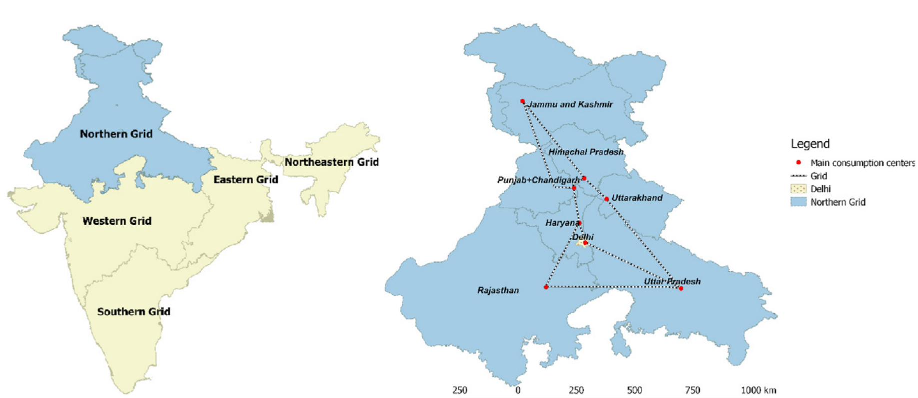

Fig. 2. Interconnected North Indian grid region comprising eight states/sub-regions.

on the modelling of the different energy sectors and the technical and financial assumptions. The LUT Energy System Transition Model [24–26] is applied across an integrated energy sector covering the demand from power, heat, transport and desalination sectors as shown in Fig. 1. A two-step approach is applied with simulation of prosumer demand with optimal annual energy cost as the first step, followed by a cost optimal simulation of the energy system covering the various sectors. The unique features of the model enable cost optimal energy system transition pathways on high levels of geo-spatial and temporal resolutions. A detailed description of the modelling process is presented in the Supplementary Material.

The model has integrated all crucial aspects of the power, heat, transport and desalination sectors, which are further described in the Supplementary Material. The technologies modelled are:

- electricity generation technologies: renewable energy (RE), fossil, and nuclear technologies;
- heat generation technologies: renewable and fossil;
- energy storage technologies: electricity and heat storage technologies;
- fuel conversion technologies: fuels for energy, mainly in transport;
- fuel storage technologies: fuel storage as part of power-to-fuels;
- electricity transmission technologies.

Fossil electricity generation technologies are coal power plants, combined heat and power (CHP), oil-based internal combustion engine (ICE) and CHP, open cycle (OCGT) and combined cycle gas turbines (CCGT), and gas-based CHP. Renewable electricity generation technologies are solar PV (optimally fixed-tilted, single-axis tracking [28], and rooftop), wind turbines, hydropower (run-of-river and reservoir), geothermal, and bioenergy (solid biomass, biogas, waste-to-energy power plants, and CHP). Fossil heat generation technologies are coal-based district heating, oil-based district and individual scale boilers, and gas-based district and individual scale boilers. Renewable energy-based heat generation technologies are concentrated solar thermal power (CSP) parabolic fields, individual solar thermal water heaters, geothermal district heaters, and bioenergy (solid biomass, biogas district heat, and individual boilers).

Storage technologies can be divided into three main categories: short-term storage – lithium-ion batteries and pumped hydro energy storage (PHES); medium-term storage – adiabatic compressed air energy storage (A-CAES) [29], and medium temperature district heat (TES DH) and high temperature thermal energy storage (TES HT) technologies; and long-term gas storage including power-to-gas (PtG) technology, which allows the production of e-methane to be utilised in the system.

Sector coupling technologies are power-to-gas including electrolysers, steam turbines (ST), electrical heaters, district and individual scale heat pumps, and direct electrical heaters. These technologies convert energy from one sector into valuable products for another sector in order to increase total system flexibility, efficiency, and decrease overall costs. A detailed overview can be found in Bogdanov et al. [25].

A detailed overview of the methods and data preparation along with the technical and financial assumptions that are considered in modelling the power, heat, transport and desalination sectors along with industrial e-fuels production and carbon dioxide (CO_2) direct air capture [30] across North India are available in the Supplementary Material (Tables S1–S4). These are based on the detailed description of the model applied to the global power sector in Bogdanov et al. [24], the coupled energy sectors in Bogdanov et al. [26], structural and technical details for the transport sector in Khalili et al. [31], demand structures for the heat sector in Keiner et al. [32], the global desalination sector in Caldera and Breyer [33] and all energy sectors in Bogdanov et al. [25]. The direct energy jobs created through the energy transition from 2020 to 2050 across North India are estimated based on the methods presented by Ram et al. [34] for the energy sector and Ram et al. [35] for the power sector (refer to the Supplementary Material for more details and results of jobs created in Figs. S28–S30).

The electricity demand for each node and each year up to 2050 is calculated exogenously based on cumulative annual growth rates for electricity taken from Bogdanov et al. [25]. The total primary energy demand (TPED) is calculated based on the Physical Energy Content Method (PECM) defined by the International Energy Agency [36]. Other methods result in different TPEDs, i.e., the Partial Substitution Method (PSM) would lead to higher TPED and the Direct Equivalent Method would lead to lower TPED, as shown by Krann et al. [37]. Therefore, this research defines primary energy as the physically obtained energy at the first extraction from nature and equates all fuels and technologies fairly on this fundamental basis of initial human action [25]. The hourly electricity load profile is calculated as a fraction of the total demand for each sub-region based on synthetic load data weighted by the sub-region's population [38]. Transmission and distribution grid losses are estimated by the method from Sadovskaia et al. [39]. Heat demand profiles classified as low, medium, and high temperature heat are generated according to the method established in Keiner et al. [32]. All demand data are presented in the Supplementary Material (Table S5). Results across all states and North India are presented in the Supplementary Material (Tables S5–S7) for sectoral energy demand, installed capacities and generation/output for all energy technologies from 2020 to 2050.

Increasing water stress, particularly across North India entails solutions that can reduce water stress and ensure ample availability to critical activities of irrigation for agriculture. In this context, desalination plays a vital role and is considered in detail in this research. The desalination demand is estimated for regions with water stress greater than 40% and is a function of the water stress and total water demand for a specific year. The water stress referred to is explained in more detail in Caldera et al. [40]. The total water demand is the sum of the projected demand from the municipal, industrial and agricultural sectors. Irrigated agriculture accounts for 70% of the global water withdrawals. However, the average global irrigation efficiency is estimated to be as low as 33% and experiences a maximum relative growth rate of 0.3% per annum. In Caldera and Breyer [33], a scenario is presented where the irrigation efficiencies are increased using a maximum relative growth rate of 1% per annum. The irrigation efficiency growth rate per annum varies with water stress, based on a logistic expression. It is assumed that irrigation sites with water stress higher than 80% have a maximum growth rate of 1% per annum. The improved irrigation efficiency results in a reduction in water demand, water stress and consequently desalination demand for a given year. This method, the data and assumptions used to project the desalination demand from 2015 to 2050 are discussed in Caldera and Breyer [41]. Therefore, the desalination demand presented addresses the demands of the municipal, industrial and agricultural sectors with improved irrigation efficiency across North India.

2.1. Regional setup for north India

The regional composition of North India considered in this study is based on the Northern power grid region of India, as shown in Fig. 2, and it is one of the five major regional power grids in the country. The region consists of eight states or sub-regions and the composition of the regional grid is:

States: Jammu and Kashmir (including Ladakh), Himachal Pradesh, Punjab and Chandigarh, Uttarakhand, Haryana, Delhi, Rajasthan and Uttar Pradesh

The eight states including Delhi are interconnected with optimised transmission networks and it is assumed that the existing network of distribution lines within the regional states ensure energy supply to all consumers in the state. A cost optimised transition pathway for an integrated energy system is modelled for a BPS across North India.

2.2. Best Policy Scenario

The LUT Energy System Transition Model can be utilised to generate wide-ranging energy scenarios across the different regions of the world on a global-local scale. However, the objective of this study is to highlight an energy scenario for Delhi within the regional grid area of North India in context of achieving the goals of the Paris Agreement by reaching zero GHG emissions from the energy sector, in a technically feasible and economically viable manner. Therefore, a BPS is envisioned for an integrated energy sector combing the power, heat, transport and desalination demands for the case of Delhi within North India, from the current system in 2020 towards cost optimal energy system with varying features by 2050. The results are visualised and presented in five-year intervals through the transition from 2020 to 2050 for an integrated energy system transition across North India in the BPS. Furthermore, the results are highlighted from an integrated energy system perspective as well as from a sectoral perspective for the power, heat, transport and desalination sectors.

3. Results

Results of the energy system transition for Delhi within the North Indian grid region from 2020 to 2050 are presented with research insights on the evolving energy demand, energy capacities and generation, storage capacities and output, various energy costs, GHG emissions development and net employment impacts along with regional and Delhi specific findings.

3.1. High electrification scenario

Urban energy systems have evolved from servicing scattered settlements with food and fuels to modern megacities with nationalised and regional energy networks [42]. However, in recent years the rise of the ‘renewable city’ has emerged from the decoupling of fossil fuels and economic growth [43]. As urban energy systems switch from fossil fuels to renewables, with wind and solar PV replacing coal and gas power plants, while fossil oil is being replaced by electric vehicles and e-fuels. This is the fundamental basis for the BPS, in which substantial penetration of renewable energy influences change in resource efficiency through rapid electrification across the different energy sectors. This eventually determines the levels of primary energy demand across North India as shown in Fig. 3. The initial gain in efficiencies is due to substitution of thermal power generation with renewable electricity, rapid electrification of the heat and transport sectors, while the growth in demand for energy services leads to higher final energy demand, despite increase in electrification. Additionally, there is a substantial demand for desalination in 2045 and 2050 to meet the growing water demand from urban centres like Delhi. The primary energy demand transitions from being dominated by fossil fuels and nuclear energy in 2020 to being substantially electricity-based by 2050, as shown in Fig. S10 in the Supplementary Material. Electrification of nearly 95% of primary energy demand across the energy sectors plays a vital role in driving the transition towards higher shares of renewable energy as well as deliver high level of energy services. On the other hand, final energy demand increases steadily as the demand for higher energy services increases from around 2000 TWh in 2020 to around 4400 TWh by 2050 (refer to Fig. S10 in the Supplementary Material).

The heat and transport sectors undergo a significant transformation in the course of the energy transition, as high levels of electrification lead to higher demand for electricity and rapid decline in demand for fossil fuels (see Fig. 4). Urban centres such as Delhi will play a key role in driving the transition in the transport sector, which will reduce the high reliance of transport on imported fossil fuels [44]. Shenzhen has emerged as a pioneer in rapid adoption of electric vehicles and is a blueprint for other megacities around the world [45].

Fossil fuels consumption in the transport sector across North India is seen to decline through the transition from about 96% in 2020 to zero by 2050. On the other hand, Fischer-Tropsch based electro-fuels (e-fuels) produced by renewable electricity contribute over 30% of the final energy demand in 2050. In addition, hydrogen constitutes about 20% of final energy demand in 2050, as shown in Fig. 4.

3.2. Electricity and heat supply

Energy supply across North India is mainly through electricity and heat, as high levels of electrification are achieved through the

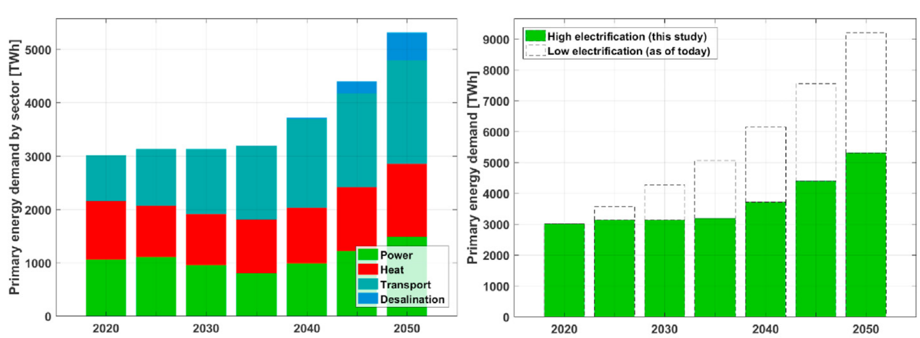

Fig. 3. Primary energy demand of the different sectors (left) and efficiency gain or reduction in primary energy demand of the high electrification scenario compared to the low electrification scenario as of today (right) during the energy transition from 2020 to 2050 across North India. The primary energy demand initially remains stable at around 3000 TWh from 2020 to 2035 and increases substantially to over 5200 TWh by 2050. A high level of electrification, which is the basis for this study indicates a massive gain in efficiency or reduction in the primary energy demand (3800 TWh) compared to a business as usual case or a low electrification scenario, wherein the primary energy demand nearly doubles by 2050.

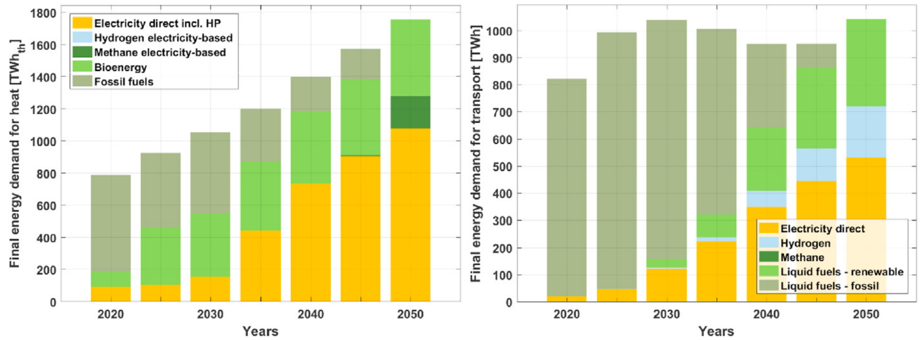

Fig. 4. Final energy demand for heat (left) and transport (right) during the energy transition from 2020 to 2050 across North India. The share of electricity in the final energy demand for heat increases substantially with around 1100 TWh by 2050, while the share of fossil fuels in the final energy demand declines from about 600 TWh in 2020 to zero in 2050. Electricity demand to provide sustainable heat increases through the transition to around 920 TWh_{el} by 2050 (more details in Fig. S16). More than 10% of the electricity is to produce e-methane, which is utilised for heat generation, mainly to satisfy the high temperature industrial heat demand. E-methane is prioritised over hydrogen, as it is an easily applicable drop-in solution.

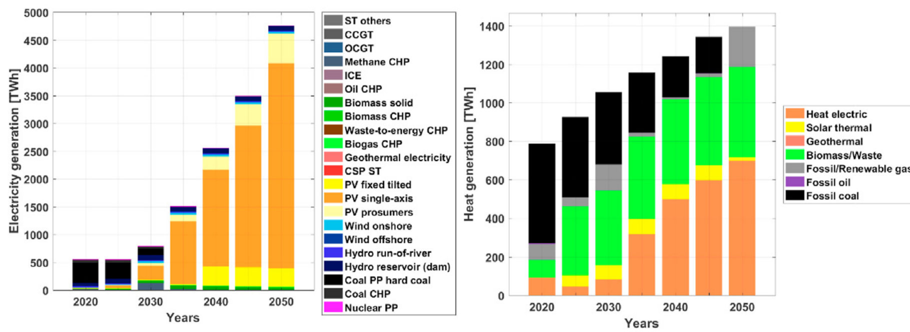

Fig. 5. Technology-wise electricity generation (left) and heat generation (right) during the energy transition from 2020 to 2050 across North India. Electricity generation from the various technologies to cover the demand of power, heat, transport and desalination sectors. Solar PV supply increases rapidly through the transition from around 39% in 2030 to about 96% by 2050, which is already the lowest cost electricity source. Heat pumps coupled with direct electric heating play a significant role through the transition with a share of nearly 37% of heat generation by 2050 on both the district and individual levels.

transition, thereby an increasing amount of electricity and heat generation is needed (see Fig. 5). The electricity generation capacity across North India satisfies demand from all energy sectors including power, heat, transport and desalination. The total installed capacity grows massively from about 100 GW in 2020 to over 2600 GW by 2050 (refer to Fig. S11). In the initial period of the transition, a larger share of coal capacities dominated the system up to 2030, but from 2035 onwards solar PV dominates the shares of installed capacities reaching over 2400 GW by 2050, as highlighted by Gulagi et al. [10] for the whole of India.

In the heat sector, heat pumps coupled with direct electric heating, and biomass-based heating constitute the majority of installed capacity by 2050 (refer to Fig. S13). A steady increase in total installed capacity of heating technologies, despite a growing demand for heat occurs mainly due to efficiency gains with heat pumps and direct electric heating, as fossil fuels recede from the energy system. District heating is scarce across North India with limited demand for space heating, however, district heating systems have a vital role in providing renewable heat across megacities of the world [46,47].

Ensuring consistent electricity and heat supply across North India is accomplished by storage technologies, both electricity storage and heat storage options that complement renewable energy adoption through the transition. The electricity storage options are presented in Fig. S12 and the heat storage options are presented in Fig. S14 of the Supplementary Material. Batteries (both utility and prosumer scale) emerge as the most cost effective solution for electricity storage, as they complement solar PV [48]. Thermal energy storage (both high temperature and DH) emerges as the key heat storage option, while gas (both methane and hydrogen) storage provides vital seasonal storage across North India.

The final energy demand of the transport sector across North India is more than the energy demand from the power sector at around 800 TWh in 2020. However, after an initial increase the demand declines and further rises to around 1200 TWh by 2050 (refer to Fig. S15). This is achieved mainly due to efficiency gains brought about by electrification of the sector and the increase in 2050 is attributed to the demand from e-fuels for the transport sector. A highly efficient transport sector is possible with a combination of direct electrification and utilisation of e-fuels by 2050 across North India including Delhi. Renewable electricity-based e-fuels are essential to fulfil energy demand mainly from the transport and heat sectors via the power-to-fuels processes. Fischer-Tropsch (FT) fuels, hydrogen and liquefied gases (methane and hydrogen) are viable alternatives to fossil fuels and have a vital role to enable the energy transition across North India. Details of renewable electricity based e-fuels are presented in Figs. S17 and S18 in the Supplementary Material.

3.3. Regional outlook

Solar PV capacities are well distributed across the different states/sub-regions of North India and along with hydropower, wind and bioenergy achieve a total installed capacity base of about 2570 GW in 2050. Moreover, there are capacities across the states/

sub-regions with excellent solar conditions throughout the year [10,11], as shown in Fig. 6. Whereas some capacities of hydropower and bioenergy are in the states of Punjab and Himachal Pradesh. The electricity generation across the power, heat, transport, and desalination sectors of North India are predominantly from PV in 2050, evenly distributed across the regions as shown in Fig. 6. Delhi derives all of its electricity from solar PV (mainly prosumers) in 2050, as fossil fuels are phased out (refer to Fig. S24 and Table S7).

Utility-scale and prosumer batteries contribute a major share of electricity storage capacities, with some shares of Adiabatic Compressed Air Energy Storage (A-CAES) by 2050, as shown in Fig. 4. Storage capacities are well distributed across the states/sub-regions of North India, mainly to complement higher shares of installed solar PV capacities. Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050, as shown in Fig. 6. A-CAES contributes complementary shares of electricity storage output through the transition, across the different states/sub-regions of North India, with higher shares in Himachal Pradesh. While Delhi is predominantly reliant on prosumer batteries to complement its numerous installations of prosumer scale solar PV across the city, mainly on rooftops.

Heat storage plays a vital role in ensuring stable heat supply across the states/sub-regions of North India, with majority of gas storage capacities installed in 2050 as shown in Fig. 6. In terms of output, thermal energy storage (TES) supplies most of the heat across North India with a total of about 1050 TWh in 2050, as shown in Fig. 6. Gas storage plays a critical role in providing seasonal storage also for balancing monsoon effects across the country [10,49], with higher installed capacities owing to the low-cost availability of storage capacities and supplying seasonal heat demand with lower output. However, it also provides crucial flexibility to the energy system with coupling the power and heat sectors.

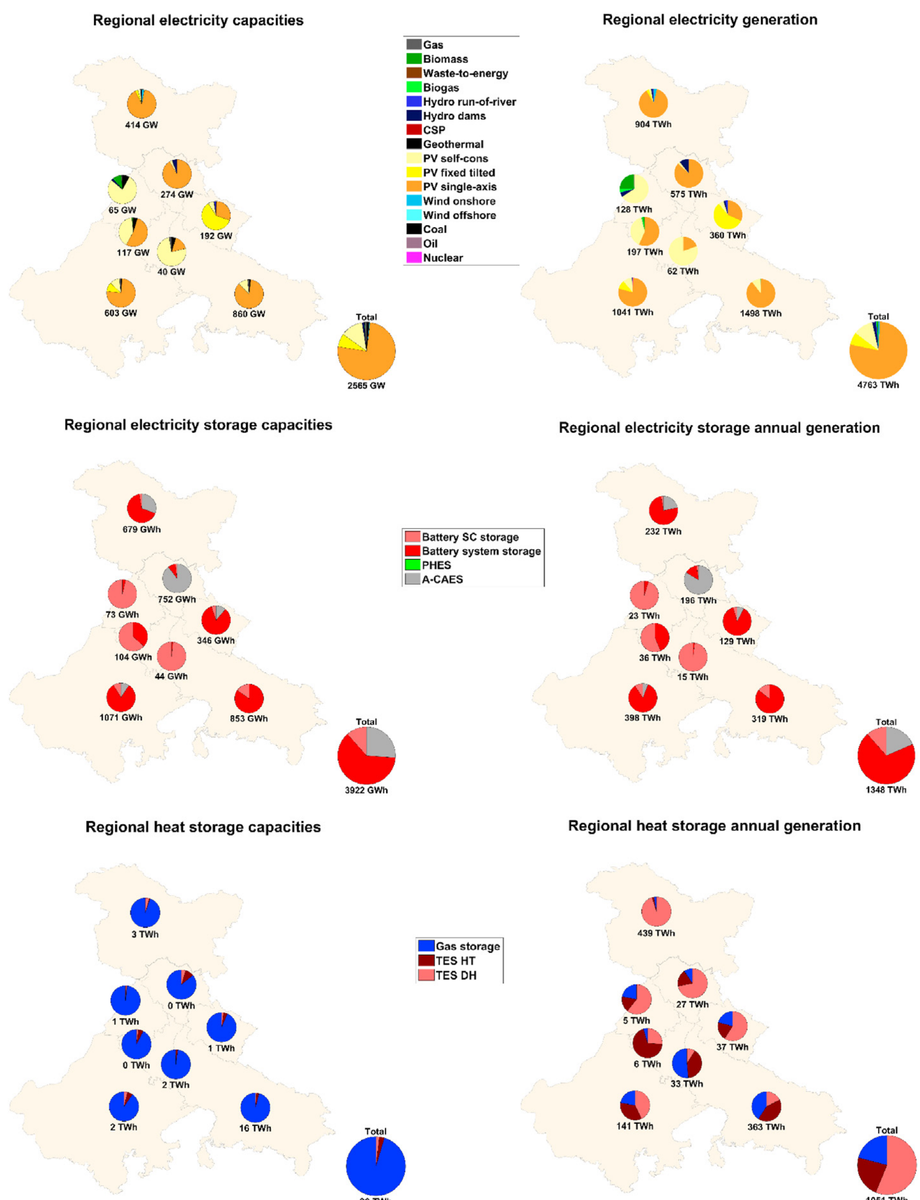

Fig. 6. Regional distribution of electricity generation capacities (top left), electricity generation (top right), electricity storage capacities (center left), electricity storage output (center right), heat storage capacities (center left) and heat storage output (bottom right) in 2050 across North India.

3.4. Outlook for Delhi

Delhi, despite having an area sprawling just 1484 km^2 has one the highest per capita energy demands in the country with per capita electricity consumption of 1750 kWh against a national average of 1200 kWh in 2020 [50]. This growing demand for energy obligates Delhi to rely on electricity imports from neighbouring states and mainly from the North Indian regional grid. However, Delhi presents a unique case in the country as it has a high share of domestic consumers with 82% of the total electricity demand from domestic households in 2020 [50,51], which is ideal for the growth of solar PV prosumers [27]. However, a substantial amount of energy used today in Delhi is still from the burning of cow dung, crop waste, biomass including wood and kerosene for heating and cooking, particularly in low-income households. In this research, these are represented by a share of energy in the heat sector for biomass-based cooking. This share of biomass-based cooking is expected to shift towards electric and modern energy services through the transition. The energy transition in Delhi is mainly driven by solar PV prosumers with nearly 80% electricity generation in Delhi by 2050 and imports from the regional grid with over 70% from 2035 to 2050 of the electricity for Delhi, as indicated in Fig. 7. This is highly plausible as highlighted for the case of New York with distributed solar PV across the city [52]. The energy system in Delhi transforms from heavily based on coal, biomass for cooking and fossil gas in 2020 towards completely based on solar PV and renewable energy imports from neighbouring states by 2050, as solar PV emerges as the least costing energy source. Electricity imports play a vital role in ensuring steady supply in Delhi, the neighbouring states in the North Indian grid region have excellent renewable energy sources and a cost optimal energy mix is imported into Delhi. The high electrification scenario across the transport and heat sectors implies a higher electricity demand in Delhi, which drives the higher shares of electricity imports from over 30% in 2020 to above 70% in 2020, as shown in Fig. 7.

A strong regional grid is vital for all states in the region as well as Delhi to benefit from the low-cost renewable energy resources in the entire region (see Fig. 8). Grid utilisation is predominantly high in the summer and the following monsoon season [49], with high utilisation during the daytimes corresponding with high solar PV generation as shown in Fig. S26. Rajasthan, Jammu & Kashmir, Uttarakhand and Himachal Pradesh emerge as net exporters, while the other states in North India are net importers with Delhi having the highest import share of over 70% in 2050. State and regional results for sectoral energy demand (Table S5), installed capacities of different energy technologies (Table S6) and generation/output of different energy technologies (Table S7) through the transition period is presented in the Supplementary Material.

In a cost optimised energy system across the North Indian grid, transmission and distribution play a vital role in ensuring all the states/sub-regions benefit and reduce the overall energy costs. This setup is extremely important for smaller in size, but huge in energy demand cities like Delhi, which imports most of its electricity through transmission from Haryana, finally exported from Himachal Pradesh. On the other hand, states such as Jammu and Kashmir (including Ladakh) emerge as a huge exporter of low-cost renewable electricity, which can economically boost the state and also create much needed jobs.

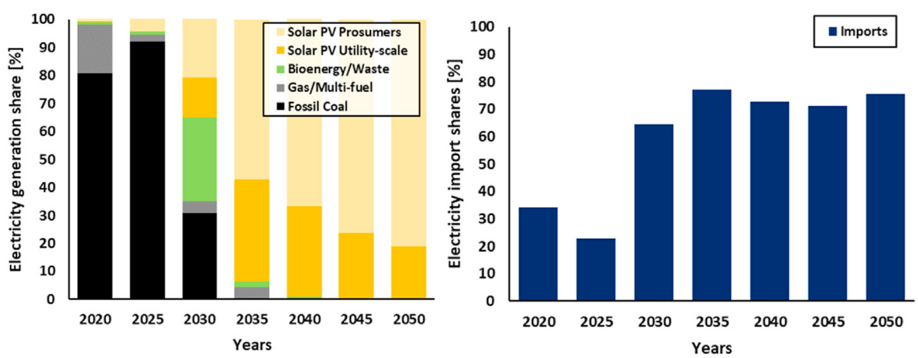

Fig. 7. Share of electricity generation from different energy technologies (left) and share of electricity imports (right) through the transition from 2020 to 2050 in Delhi.

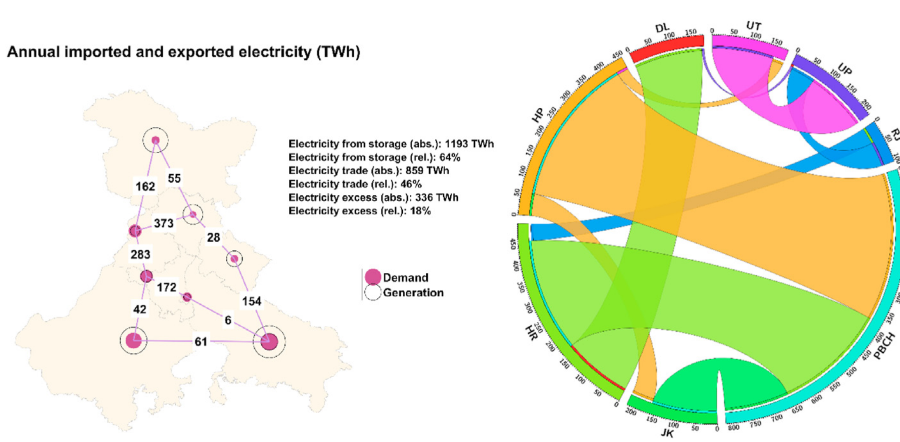

Fig. 8. Regional electricity exports and imports (left) and interregional exchange of electricity (right) across North India in 2050. The annual net cross-regional grid utilisation across North India is around 859 TWh, which is 20% of the electricity generated in 2050.

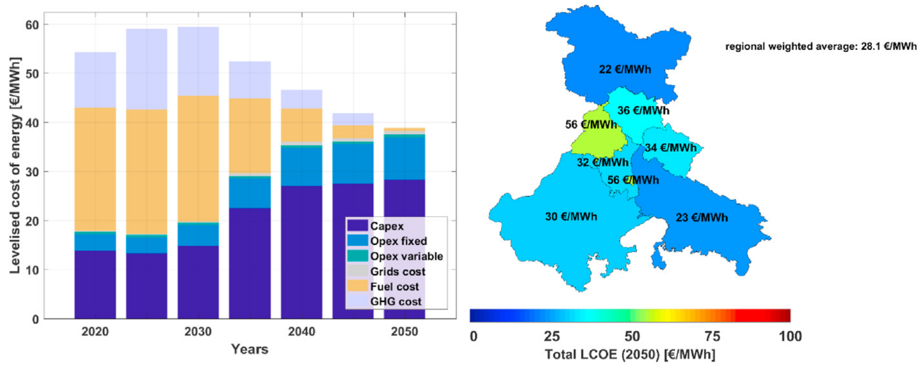

Fig. 9. Levelised cost of energy across North India during the energy transition from 2020 to 2050 (left) and the regional variation of the levelised cost of electricity in 2050 (right).

3.5. Cost optimal energy transition pathway

As increasing shares of power generation capacities are added globally, renewable energy sources on a levelised cost of electricity basis become the lowest cost power generation sources [53]. As indicated in Fig. 9, levelised cost of energy declines to around 39 €/MWh by 2050 and is increasingly dominated by capital costs, as fuel costs continue to decline through the transition period, which could mean increased self-reliance in terms of energy for North India by 2050. Capital costs are well spread across a range of technologies with major investments in solar PV, batteries, heat pumps, and e-fuel conversion capacities up to 2050, similar to the analysis for India [10,11]. Most of the investments are in the later periods of the transition from 2035 onwards, as the energy system requires more flexibility solutions with higher shares of renewables. Investments in the range of 350 b€ would be required in the period 2045–2050 with average annual investments through the transition at around 50 b€ per annum, more details for investment costs in Fig. S20, electricity costs in Fig. S21, heat costs in Fig. S22 and transport costs in Fig. S23 in the Supplementary Material.

The average regional cost is a more accurate representation of the cost of the energy system, with an effective cooperation of states in the region to achieve the least cost energy system for the entire region. Delhi would import low-cost renewable electricity from neighbouring states, as this is the least cost solution for the entire region, but finally also for Delhi. This could be achieved with direct investments from Delhi in neighbouring states, or power purchase agreements (PPAs), or other forms of longer term contracts. This would finally equalise the cost levels, as indicated for the total region. Fig. 9 is a pure supply perspective, while from a demand perspective the equalised average cost level of 28 €/MWh is the more realistic electricity trading outcome in 2050. The opportunities for low carbon investments in cities are immense [54] and as highlighted the amplification of these investments can drive energy transitions regionally as well as nationally.

3.6. Desalination to address water stress across north India and Delhi

India is amongst the most water stressed countries and ranks 13th for overall water stress and has more than three times the population of the other 17 extremely highly stressed countries combined [12]. Groundwater tables in some northern aquifers declined at a rate of more than 8 cm/annum from 1990 to 2014 [12], due to rampant extraction. Almost 90% of India's thermal power generation depends on freshwater for cooling [55] and this competes with water for irrigation and amplifies water stress to a great extent. Delhi too is amongst the most water stressed cities in the world [56]. Therefore, seawater desalination based on renewable electricity along with other solutions including more efficient irrigation; conserving and restoring lakes, floodplains, and groundwater recharge areas; and collecting and storing rainwater, could be pursued to reduce water stress across the country as well as in Delhi. With the transition towards higher shares of renewables, water stress induced by thermal power generation can be eliminated across North India as well as the whole of India, as demonstrated by Lohrmann et al. [57].

The installed desalination capacities increase from 2040 onwards to more than 180 million m^3/day providing around 65 trillion m^3/annum of desalinated water in 2050, as highlighted in Fig. 10.

3.7. Climate compliant and just energy transition pathway

The results of the energy transition towards high shares of renewable energy indicate a rapid decline in GHG emissions, reaching zero by 2050 in comparison to current levels of 825 $MtCO_{2eq}$/a in 2020, across the power, heat and transport sectors in North India as shown in Fig. 11. In the case of Delhi, emissions peak in 2025 with about 62 $MtCO_{2eq}$/a in 2020 and reach zero by 2050. The energy transition pathway across North India including Delhi is in line with the ambitious Paris Agreement target of limiting temperature rise to 1.5 °C in comparison to pre-industrial levels with zero GHG emissions by 2050. GHG emissions from the power, heat and transport sectors are highlighted in Fig. S27. Similar to GHG emissions, the level of air pollution is expected to decline through the transition to near zero by 2050, therefore contributing to reducing associated health impacts across the region, which has both societal as well as economic benefits.

Along with GHG emissions, air pollution is a pertinent issue particulary in Delhi, which is suffering form the consequences of high levels of air pollution [58,59]. Air pollution in turn is responsible for substantial health impacts and corresponding health costs. An energy transition across the North Indian region can provide the impetus to enable decline in air pollution in Delhi and the region. Galimova et al. [60] quantify the benefits of declining air pollution through a global energy transition with corresponding decine in mortaility rates and damage costs. Jacobson et al. [15] have quantified savings of up to 48 cents USD/kWh in terms of health costs enabled by avoided air pollution impacts and avoided premature mortalities induced by air pollution at over 37,000 to nearly 53,000 per year in Delhi with 100% renewables by 2050.

The energy transition across North India will create a substantial number of jobs, with the total number of direct energy jobs set to increase rapidly from about 1.8 million in 2020 to just over 4.4 million by 2050, as highlighted in Fig. 12. The sectoral and category-wise distribution of jobs across the energy value chain created in North India through the transition period is shown in Fig. 12. The

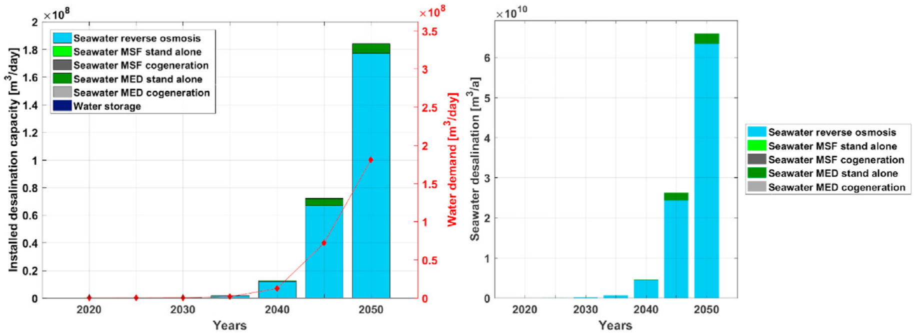

Fig. 10. Installed capacities for desalination and water demand (left) and annual desalinated water (right) during the energy transition from 2020 to 2050 across North India.

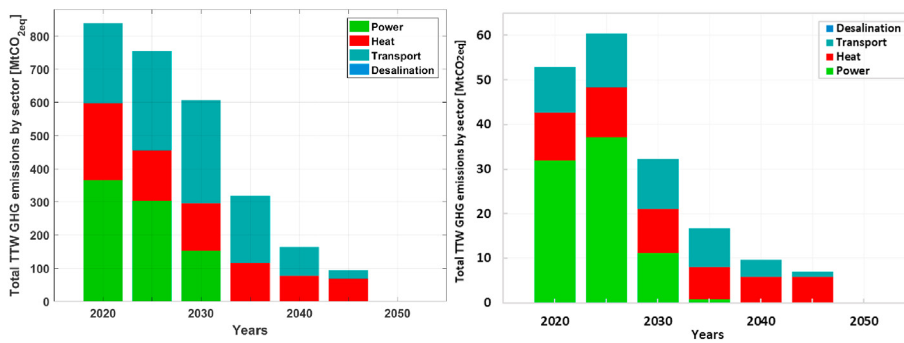

Fig. 11. Sector-wise GHG emissions during the energy transition from 2020 to 2050 across North India (left) and in Delhi (right). Tank to Wheel (TTW) considers GHG emissions from readily available fuels and does not consider GHG emissions from the upstream production and delivery of fuels. GHG emissions from the power sector decline through the transition from around 375 $MtCO_{2eq}$/a in 2020 to zero by 2035. Similarly, GHG emissions from the heat sector decline through the transition from about 225 $MtCO_{2eq}$/a in 2020 to zero by 2050. GHG emissions from the transport sector decline through the transition from around 225 $MtCO_{2eq}$/a in 2020 to zero by 2050.

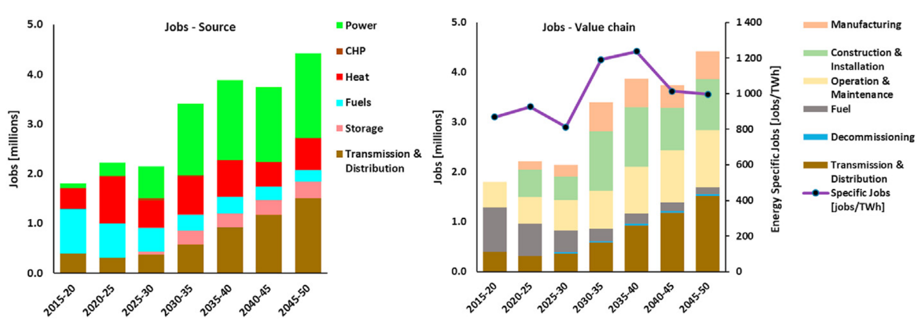

Fig. 12. Jobs across the different energy sectors (left) and jobs across the energy value chain with the development of energy demand specific jobs (right) during the energy transition from 2020 to 2050 in North India.

power sector along with the transmission and distribution of electircity emerges as the prime job creators across the region by 2050. Jobs associated with manufacturing, construction and installation as well as operation and maintenance increase through the transition, whereas jobs asscosiate with fossil fuels decline. However, there are significantly more number of jobs created than lost during the transition. This is also indicated by the final energy demand specific jobs that have a net increase by 2050.

Detailed insights on job creation associated with power, heat and fuels through the transition are presented in Figs. S28–S30, in the Supplementary Material.

The cost-optimal solution for the entire North Indian grid including Delhi consists of over 2225 GW of utility-scale solar PV and about 12 GW of onshore wind. This entails land requirement of about 24,270 km^2 for solar PV and about 1430 km^2 for wind, based on PV module efficiency increase from about 19% as of 2020 to about 30% in 2050 [61] and present area demand for utility-scale PV plants according to Bolinger and Bolinger [62] leading to 85.5 MW/km^2 (fixed tiled) and 58.9 MW/km^2 (single-axis tracking) in 2020 and 135.0 MW/km^2 (fixed tiled) and 93.0 MW/km^2 (single-axis tracking) in 2050, and 8.4 MW/km^2 for wind power plants through the transition [63]. The total land required for utility-scale solar PV is around 7% of the land area of Rajasthan, the desert state with excellent solar resources. Just 7% of the land area in Rajasthan can power the whole of North India including the energy hungry megacity of Delhi. This suggests that land availability is not a constraint for 100% renewable energy systems across India.

4. Discussion

A paradigm shift is observed through the transition, wherein low-cost renewable electricity emerges as the energy carrier of the future by replacing fossil fuels, which entails significant structural changes for megacities such as Delhi.

4.1. Electrified cities to drive energy transition towards 100% renewables

In a highly digitalised future with strong climate policies, electrification of energy services will be pervasive in India as well as globally, led by megacities like Delhi [5,64,65]. One aspect that the pandemic COVID-19 has reinforced is the importance of electricity as an energy carrier [66], it was the one source of energy to keep society functioning through situations such as lockdowns [67]. This obligates countries such as India and megacities such as Delhi and others to drive forward the trends of electrification and develop local renewable energy resources to decouple from expensive overseas imports of fossil fuels, increase energy security and resilience [68]. The most important energy carriers in future energy systems are electricity, based on renewables, followed by hydrogen, based on renewable electricity. This is precisely the strategy for the states in North India as well as Delhi to adopt, thereby shifting its heavily fossil reliant transport sector towards being more sustainable along with other urban mobility measures [44,69]. This will not only solve the increasingly toxic air pollution issue, but also reduce the growing fossil fuel import bill for Delhi, the region as well as the country.

4.2. City-region-Nation energy transition pathways

The cities and climate change conundrum is widely researched with growing interest, as indicated by literature reviews from Lamb et al. [8] and Bibri and Krogstie [65]. Moreover, there have been studies that have suggested the vital role of urban energy systems in driving sustainable development [70–72] and there are a range of urban climate solutions [73]. However, a comprehensive energy transition pathway for a megacity with its surrounding region will help stakeholders realise, analyse and develop regional plans to transform other cities around the world, which is also demonstrated for the case of Aalborg within the energy system of Denmark [47]. The results of this research enable energy transition pathways that maximise utilisation of locally available renewable resources in a cost optimal manner. Particularly important for megacities such as Delhi, with limited land space and resources and dependant on imports from the surrounding regional grid. A similar approach is adopted for low energy density cities in China [74] and broader 100% renewable energy systems are highlighted within national and regional energy systems across 53 cities and towns in North America [75] and 74 metropolitan areas and 30 megacities globally [15]. Delhi is among the 30 megacities analysed by Jacobson et al. [15], that concur a 100% renewable energy system for the city in 2050. While the energy mix in Ref. [15] has higher shares of wind energy (over 43%) compared to this research that indicates Delhi will be dominated by solar PV with majority share of prosumers. This is mainly due to least cost electricity from solar and a lack of good wind resources in the vicinity of Delhi. However, the results of Jacobson et al. [15] and this research indicate close to 50% decline in primary energy demand or end-use energy [15] by 2050, driven by high levels of electrification across the different energy sectors. This research demonstrates how regions with coal for power and imported oil for transport as the most dominant sources of energy can transition towards 100% renewables in a cost optimal and economically beneficial manner. In addition, this research highlights that cities offer some of the best climate mitigation opportunities with the adoption of solar PV prosumers across buildings, electric vehicles and e-fuels for transport, renewables based desalinated water, and waste-to-energy conversion. Also highlighted by Thellufsen et al. [47], energy transitions towards renewable energy will have to operate on different geographical scales, which is substantiated in this research with the complex energy system of Delhi reliant on the excellent renewable resources of the surrounding states that are facilitated by the North Indian grid. The North Indian grid is further expanded by the national grid network covering the whole of India [10]. This research highlights many of the concrete steps to be addressed at the local level in Delhi, while aligning with the broader regional and national energy perspectives.

5. Conclusions

A political capital such as Delhi can set an example for other megacities around the world by driving the energy transition locally as well as regionally, as it stands to benefit from a regional energy transition across North India substantiated by the findings of this research. The steady increase in capital intensive energy system costs indicate that fuel imports and the respective negative impacts on trade balances will fade out through the transition across North India including Delhi. On the other hand, domestically produced e-fuels will plug import deficits and further reduce costs. In addition, a low fuel import dependency will lead to a higher level of energy security across Delhi, the region, and the country. It is therefore necessary to develop methods that enable megacities to assess the compatibility of local renewable energy strategies in context to the surrounding regional, national and global energy systems [47,74]. However, the transition of urban energy systems is intertwined with social, geographical, technical and economic dimensions of urban settings that have to be acknowledged and integrated into future planning and decision-making [76].

In consideration of these recent trends, decision-makers across the world and specifically India and the corresponding regions and cities, increasingly seek out energy transition analyses on high geospatial and temporal resolutions, along with technical and economic details. Circumstantially, this research presents an energy transition pathway encompassing the regional grid of North India with the megacity of Delhi in a Best Policy Scenario, which is required for a comprehensive discourse on megacities driving ambitious long-term plans in a post pandemic economic recovery as well as towards global leadership in climate action. The COVID-19 pandemic began as a public health crisis that has now developed into a social and economic crisis, which has shone light on the prevalent inequalities and vulnerabilities across the cities of the world. Therefore, cities cannot afford to continue with business as usual, but need to build back greener and better with an energy transition towards higher shares of renewables and sustainability at its heart.

CRediT authorship contribution statement

Manish Ram: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Ashish Gulagi:** Methodology, Investigation, Data curation, Writing – review & editing. **Arman Aghahosseini:** Investigation, Data curation, Writing – review & editing. **Dmitrii Bogdanov:** Methodology, Investigation, Software. **Christian Breyer:** Conceptualization, Methodology, Investigation, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2022.06.073.

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