H_2 Valleys: Opportunities and Trade-offs

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(The author list provided assumes no particular order as every individual contributed to the successful execution of the project.)

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H_2

Executive Summary

Since the post-industrialisation era, we have witnessed several iterations of the hydrogen hype cycle. The proponents of the most abundant element have touted it to work miracles. However, owing to hydrogen's thermophysical properties, these hypes have fizzled out without materialising into any meaningful endeavour. It augers well that with increased renewable energy dependency, countries are now re-examining the role of hydrogen economy for energy independence through green hydrogen production. Now, in India, a functioning hydrogen economy is expected to bolster the energy portfolio in a sustainable way with the support of conducive policies (National Green Hydrogen Mission) from the Government.

With the voluntary commitment to achieve net-zero emissions, the Government of India has cemented its position as a climate leader globally. To realise this ambitious goal, various stakeholders must unite and implement strategies concurrently. A concept around creating a fledgling hydrogen ecosystem is the need of the hour—an ecosystem where producers, consumers, and allied partners play a pivotal role in maximising green hydrogen penetration in India. This study is a preliminary assessment of hydrogen (H_2) valleys, an ecosystem created across the country to achieve the green hydrogen goal.

The need for hydrogen economy is discussed with overarching narratives that provide intersectionality between hydrogen augmentation and climate mitigation. This narrative signifies the benefits and trade-offs of pursuing hydrogen-oriented interests. Data collection, baseline estimation, demand projection, and the analytical framework employed are steps in our methodology.

Using Right to Information (RTI) Act and secondary literature, baseline data were derived and the rationale for the choice is provided. A three-pronged approach was undertaken to estimate the variance in results between each of these approaches. The end result is corroborated demand data, which is essential to create projections until 2030. These projections are driven by observed market signals and expert solicitation. Three key observations are as follows:

i. Refineries and fertilisers are expected to drive the demand for hydrogen until 2030. Since a captive market is already functional, the demand for green hydrogen until 2030 will be equivalent to 25% market share while the remaining 75% will be driven by the grey hydrogen market.
ii. Green hydrogen usage will start to increase around 2025 compared to its nascent stages today. Post-2030, green hydrogen penetration will begin at scale in sectors such as freight mobility, industry (hard to abate), and city gas distribution networks.
iii. We expect the hydrogen market to demonstrate a 50:50 share by 2047 with respect to the grey and green hydrogen share. Fiscal instruments coupled with necessary policy impetus and amenable market conditions will drive this demand to new heights.

The analytical hierarchy process (AHP) is used to identify suitable land for creating H_2 valleys. It uses criteria (Table *2*) driven by priorities to maximise the use case across three areas of the hydrogen ecosystem: production, consumption, and storage/transportation. Thirteen states are identified to foster H_2 valleys, with an estimated potential of ~7 million tonnes of green hydrogen production by 2030. Key performance indicators of H_2 valleys are discussed to provide the likely electricity, water, and land footprints of these valleys.

Contents

The Need for Hydrogen Economy

To ameliorate the effects of climate change, countries around the world have pledged (Nationally Determined Contributions) to minimise their emissions (either absolute or relative to agreed measures such as gross domestic product [GDP]) by 2030, vide the Paris Agreement. In this context, India announced to reduce its emissions intensity to GDP by installing fossil-free power generation capacity and creating carbon sinks. The voluntary commitment was recently revised and submitted, considering other related parameters. These revisions are predicated on India's ability to bolster the renewable energy (RE) sector, witnessed by the continuous increase in the RE installed capacity. Therefore, targets have been revised to achieve around 50% of fossil-free generation capacity by 2030. Consequently, the resulting emissions intensity to GDP is also expected to reduce to the committed level of 45% in comparison to the 2005 levels.

Furthermore, India has also expressed the intention to achieve net-zero emissions by 2070. It is improbable to realise these goals without the service of alternative fuels and technologies such as hydrogen and carbon capture, utilisation, and storage (CCUS). Hydrogen has seen its fair share of hype cycles since the pre-industrialisation era. However, its thermophysical properties in the areas of storage and retrieval have presented untenable challenges for considering it a mainstream fuel. This perspective has begun to change for the better, primarily with the advent of advanced technologies. Improvements in sustainable ways of producing hydrogen have given a new ray of hope for countries that aim to decouple emissions pathways and energy demand.

By and large, establishing a functioning economy around hydrogen will prove advantageous in three ways:

i. *Energy security*: Our ability to disinvest fossil fuels will provide a platform to create fuel independence predicated on the growth of renewable energy.
ii. *Sectorial decarbonisation*: To achieve carbon neutrality, sectors dependent on fossil fuels, such as coal and natural gas, must shift to a capable fuel, such as hydrogen, for their thermal energy needs.
iii. *Global leader in electrolyser and green H_2 export*: While it is important to align our goals to a milestone such as the Paris Agreement, the overarching goal is to create an ecosystem that will make India a global leader in indigenous electrolyser manufacturing for a green H_2 export-driven economy post-2030.

This study examines the scope for creating H_2 valleys, identifies likely states that will lead the effort, and quantifies key performance indicators such as water, energy, and land footprints to realise the goal. To strengthen the case for the need for H_2 valleys, baseline demand was created using stoichiometric and weighted approaches, determined by current performances of demand sectors. Subsequently, these data points were used to project demand until 2030 across different states to determine their role in the near- and long-term horizon.

Approach

A four-stage process (see Figure 1) is envisaged in this work to quantify the present demand centres, project this demand to 2030, and identify the most suitable sites to set up H_2 valleys based on an analytical framework. As preliminary work to estimate baseline demand, the available literature was referred, and empirical correlations were drawn to quantify the typical consumption of H_2 in all demand centres—primarily, refinery and fertiliser units. In a refinery, hydrogen is mainly used to upgrade crude stream by sulphur removal, metal and halide removal, saturation of olefins, aromatic saturation, isomerisation, removal of nitrogen and oxygen, decyclisation, and cracking to give lighter hydrocarbons. Typically, hydrogen consumed is 1 weight% of the crude processed in modern refineries (Ramachandran, 1998).

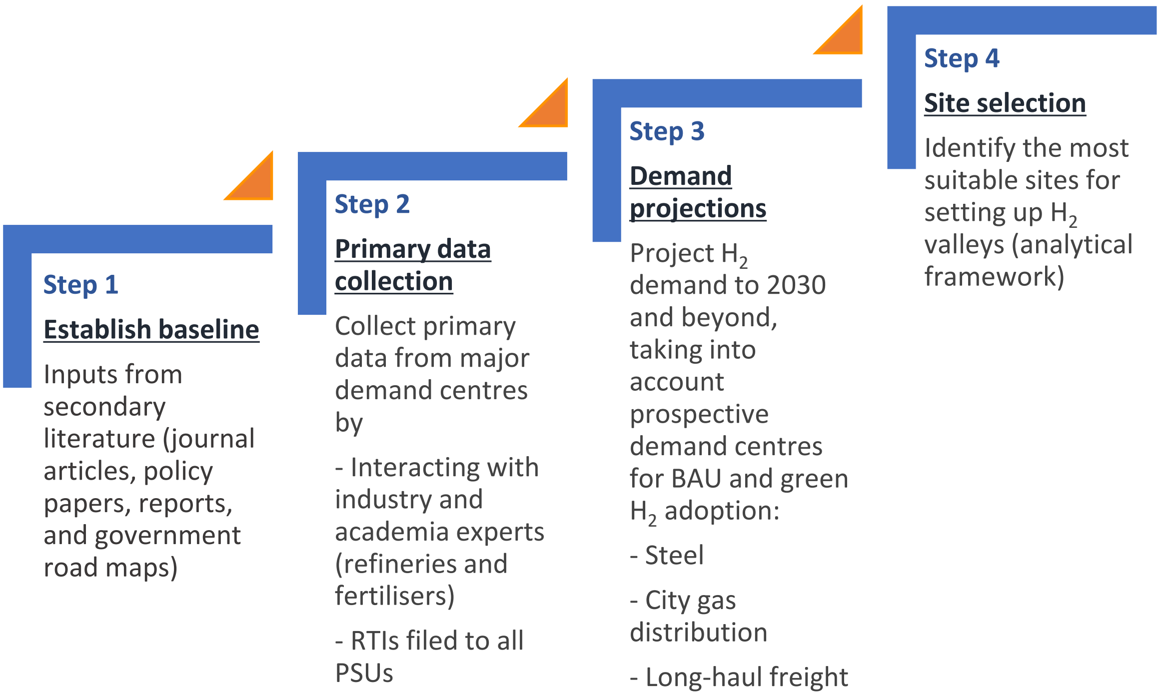

Figure 1: Approach

An alternative stoichiometric approach is employed, where it is assumed that the H_2 consumed in a refinery is primarily to remove sulphur from crude oil to meet emissions standards. In this scenario, it is estimated that 870 kg of H_2 is required to remove one tonne of sulphur (Will Hall, 2020). The crude oil in the Indian basket comprises a mix of sour grade (Oman & Dubai average) and sweet grade (Brent dated) processed in Indian refineries in the ratio 75.62:24.38 during 2019–20 (Petroleum Planning and Analysis Cell, 2022).

Considering typical values of sulphur content in sour (Oman & Dubai average) crude and sweet crude (Brent Dated) grade (EIA, 2012), the weighted average of sulphur in crude oil refined in India is computed to be 1.73%.

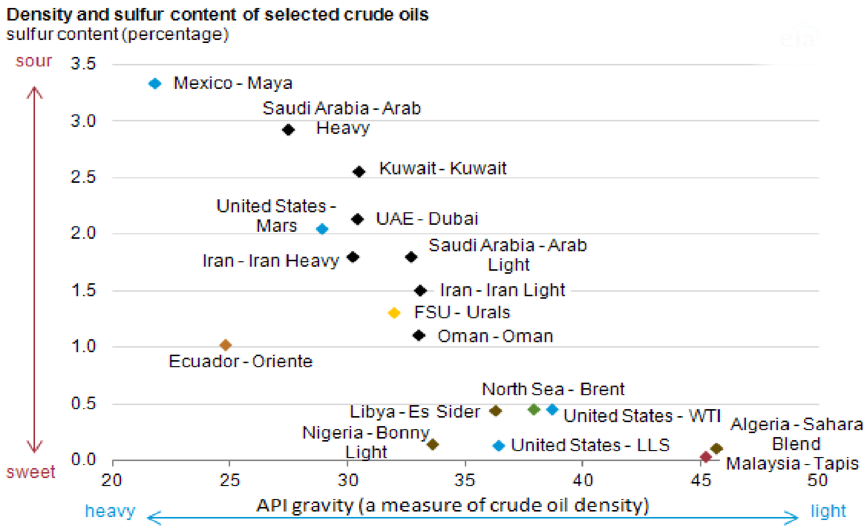

Figure 2: Sulphur content in crude oil—region-wise distribution

(Source: Energy Information Administration)

Ammonia manufacture consumes the major bulk of hydrogen in the fertiliser industry, where ammonia is the major intermediate in providing a nitrogen source for nitrogen-based and complex fertilisers having a varying percentage of nitrogen, in addition to phosphorous and potassium. Urea is the predominant nitrogen-based fertiliser, with diammonium phosphate being the most used complex fertiliser in India (Ministry of Chemicals and Fertilizers, 2019). Based on a similar stoichiometric approach, the consumption of hydrogen is computed and recorded.

To corroborate the findings of the preliminary analysis, primary data collection was undertaken by approaching public sector refineries and fertiliser undertakings. This was done by soliciting relevant information from public sector companies by means of the RTI Act.

The responses obtained from the organisations were then used to validate the preliminary research and calculate variance in data.

Table 1: Estimated variance between two stoichiometric and weight-based methods

H_2 demand centres	**Approach**			**Variance (%)**	
	Stoichiometric (A)	Weight-based (B)	Secondary literature (C)	B to A	B to C
Refineries	3.53	2.70	2.83	23.4	4.6
Fertilisers	2.46	2.55	N/A	3.5	N/A

The high degree of variance in refinery data between the stochiometric approach and the weight-based approach can be attributed to assumptions taken in computing the sulphur content in the Indian basket of crude oil. Further, minor inconsistencies in the RTI data need to be analysed further; for instance, discrepancies in the H_2 purging rate with consumption and generation rates were observed. However, the variance is found to be within an acceptable range of less than 5% when the RTI data are compared against secondary literature. The variance in hydrogen consumption data for fertilisers is found to be in the acceptable range.

Once the baseline data are established, the consumption patterns of hydrogen are projected to 2030, considering newer potential demand centres, including iron and steel, freight transport, and city gas distribution (GAIL, 2022). It is expected that there will be a gradual growth in the generation of green hydrogen because of policy initiatives and favourable costs as volumes increase.

Using an analytical framework developed by employing the analytical hierarchy process (AHP) in the geographic information system (GIS), potential areas for developing H_2 valleys are identified. AHP allows us to analyse multiple criteria that play a vital role in establishing H_2 valleys across the country. A GIS-based framework allows us to plan for a suite of cross-sectorial linkages that can often be overlooked in an alternative method of analysis. Furthermore, it provides seamless connectivity with AHP-based analytical data for effective visualisation of results.

Demand Projections

To examine the role of hydrogen in a future low-carbon India, demand projections have been produced for the hydrogen industry. The present hydrogen demand is primarily from two sectors: fertilisers and refineries. A bottom-up approach is employed by individually analysing these sectors for their growth until 2030. In the future, this demand is expected to grow, and potentially new demand centres are expected to come up.

As it stands, it is expected that in 2030 (see Figure *3*), the reliance on grey hydrogen will continue to grow, with major consumers being, predominantly, fertilisers and refineries. The increase in demand is to be met by emerging green hydrogen technologies that will progressively become economical to use as the scale of production increases. Further, a policy push from the government will necessitate green hydrogen purchase obligations for industries, thereby increasing the green hydrogen component in the overall hydrogen economy.

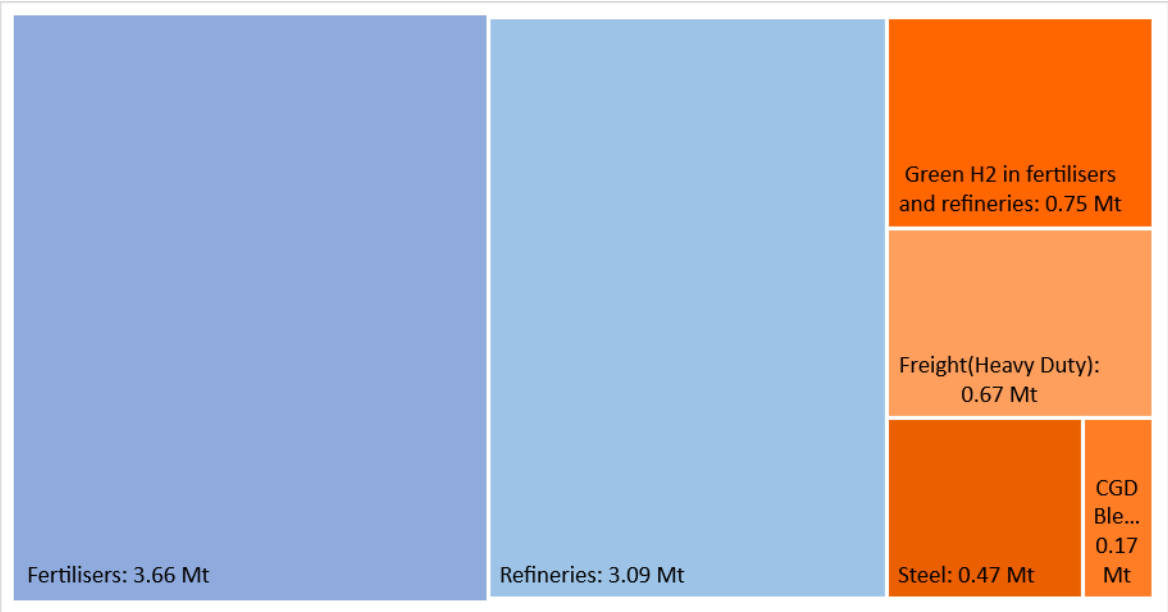

Figure 3: H_2 sectorial demand 2030

Three sectors are expected to play a key part in generating demand for hydrogen, viz. the steel industry, the road transportation sector (with emphasis on the long-haul freight sector), and the city gas distribution blending sector.

Hydrogen is expected to play an important role in the steel industry. It will be used as a source of energy and a reducing agent (Hybrit, 2022). Hydrogen demand is also expected to rise in the road transportation sector, particularly in long-haul heavy-duty vehicles. This mainly comprises trucks and buses, used mostly in freight operations. Further, to reduce natural gas emissions and costs, it is expected that the blending of hydrogen to city gas distribution networks will potentially develop as a demand centre.

Analytical Hierarchy Process

To identify suitable land required to create hydrogen valleys across India, we need a multi-criteria decision-making (MCDM) framework, such as the analytical hierarchy process (AHP). Typically, AHP accounts for a collection of options (criteria) ranked in order of preference based on the significance/relevance of the options to the problem (Djilali Messaoudi, 2019). In this case, we used AHP to identify land for creating H_2 valleys. To do so, there is a need to identify a basket of criteria with an assigned role in the hydrogen ecosystem. Upon identification, they are prioritised using a pairwise comparison strategy.

There are four steps in AHP: identify criteria, conduct pairwise comparisons, estimate the priority weight of each criterion, and shortlist the best option using computed *utility*.

Criteria: To identify suitable land parcels across India conducive for establishing H_2 valleys, we have created a basket of nine criteria (see Table *2*) that are linked to at least one of the three parts of the hydrogen ecosystem.

Table 2: List of criteria and rationale

Criteria	H_2 Ecosystem	Rationale
Proximity to steel plants	Consumption	Potential demand centre for H_2
Proximity to fertiliser plants	Consumption	Major consumer of H_2
Proximity to refineries	Consumption	Major consumer of H_2
Availability of surface water	Production	Raw material / input for electrolysis
Proximity to substations	Production	Source of electricity for electrolysis
Proximity to chlor-alkali units	Production	Generate H_2 as a by-product
Distance to highways	Storage/transport	Facilitate easy transport of compressed H_2
Access to railway lines	Storage/transport	Facilitate transport of compressed H_2
Access to gas pipelines	Storage/transport	Facilitate transport through pipelines; access to possible city gas distribution

Upon identifying the criteria, a *pairwise comparison matrix* is created. A number is assigned to each criterion, which indicates the relative importance (priority) of the compared criteria. This number is generally between 1 and 9. For instance, if 1 is assigned, it denotes that both criteria are equally preferred. Similarly, 7 and 9 denote very strong and extreme levels of preference, respectively. Even numbers represent uncertain levels of preference (equal, moderate, strong, very strong). Such circumstances require negotiations between contributors until an odd number is assigned[1]. In case if a consensus cannot be arrived at, a middle point is determined as a solution.

A completed pairwise comparison matrix is then *normalised* using computed average (for each row of criterion). This average is used to determine the priority vector required to conduct consistency analysis.

[1] In the preliminary version, we assigned values that led to natural consensus. However, when more stakeholders are included in the analysis stage, we expect negotiations to indicate the need for any given criteria to govern the nature of preference.

Once the pairwise consistency matrix is normalised, the matrix is checked for consistency. The consistency ratio (CR) is the metric that measures the consistency of pairwise comparisons. The priority vector is calculated, and the principal eigenvalue is calculated from the pairwise comparison matrix. The consistency index (Jose Antonio Alono, 2006) is given by the equation

$$CI = \frac{\lambda_m - n}{n - 1},$$

where λ_m is the principal eigenvalue and *n* is the number of criteria considered for decision-making.

Subsequently, consistency ratio is determined as

$$CR = \frac{CI}{RI},$$

where RI is the random index (Koichiro Aoki, 2016), which is a factor that is dependent on the number of criteria being evaluated. This value, corresponding to the number of criteria evaluated, is taken from the literature. The matrix is accepted to be consistent if consistency ratio is less than 0.1.

Hydrogen Valley 1.0

The interplay of demand, supply, transport, and storage elements in a hydrogen economy determines the need for H_2 valleys in India. Since the hydrogen sector is largely captive, refineries produce hydrogen to meet requirements. Any additional quantities will be sold to other refineries or fertiliser manufacturers. However, with a robust market in place, the demand for hydrogen is expected to diversify in coming years, especially in avenues where fossil fuel intake is noticeably high. Based on the approach and designed AHP, a preliminary version of a H_2 valley is depicted in Figure 5 (Department of Fertilisers, 2018; AMAI, 2017; Ministry of Steel, 2022; Energy Map of India, 2021; MOPNG, 2022).

A total of 13 states (see Figure 5) were identified for establishing H_2 valleys. These states are Rajasthan, Gujarat, Maharashtra, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, West Bengal, Assam, Haryana, Punjab, and Goa. As the area shortlisted in Goa seemed negligible compared to other states, it is not included in Figure 5. A state-wise representation of the H_2 valley is provided in Appendix I.

These 13 states are expected to account for around 75% (see Figure 4) of hydrogen production and consumption. The criteria list accounted in this analysis may have resulted in the exclusion of states such as Uttar Pradesh, Bihar, and Madhya Pradesh. As we continue to refine the analysis with additional criteria based on expert solicitation, some of these states may get added and their respective areas will be accounted towards H_2 valleys in future versions. It is important to note that these results are from a working version, which is subject to change.

Around 8.8 Mt of green hydrogen is expected to be the market demand by 2030. This potential is ascertained based on current demand, estimated using approaches mentioned in Table 1. Under the business-as-usual scenario, the baseline demand estimated is projected to create a total demand of around 6 Mt of green hydrogen from these identified valleys.

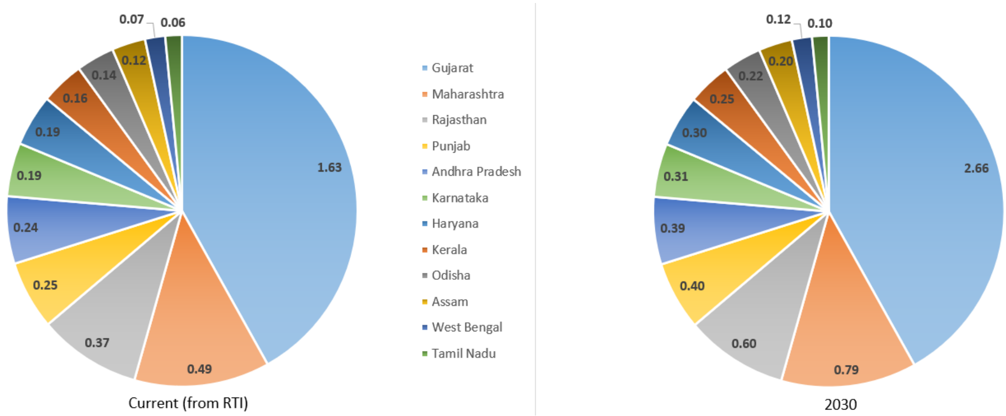

Figure 4: Current and projected hydrogen demand

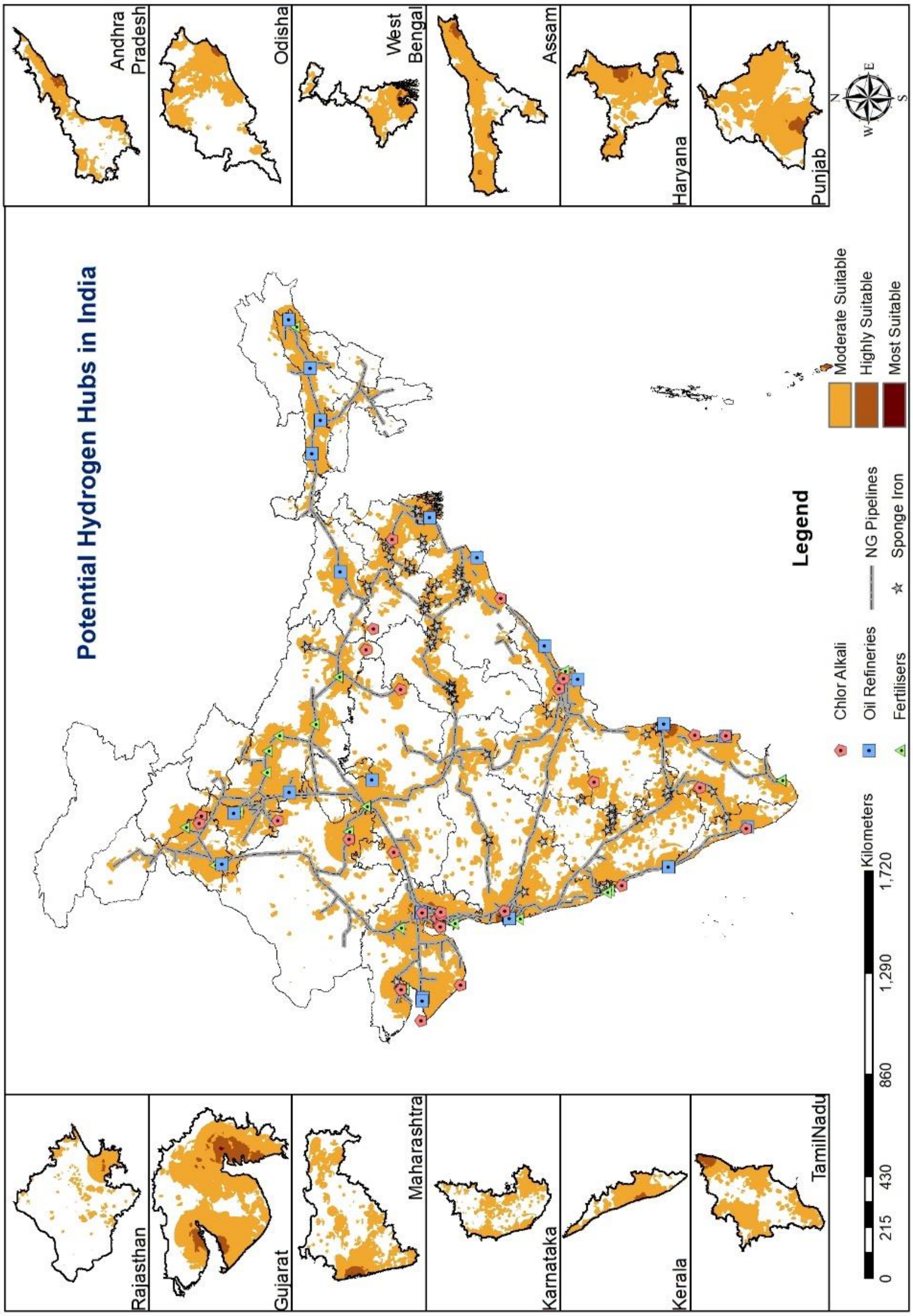

Figure 5: Hydrogen Valley 1.0

Key Performance Indicators

The multi-criteria analysis yielded a list of 13 states that have regions which are conducive to green hydrogen generation, significant number of hydrogen consumers in their proximity, and accessible modes of transport for transfer of hydrogen as required. Based on this analysis, each of these 13 states is evaluated against key performance indicators (KPIs; see Figure 7) for H_2 valleys, namely land, water, and electricity.

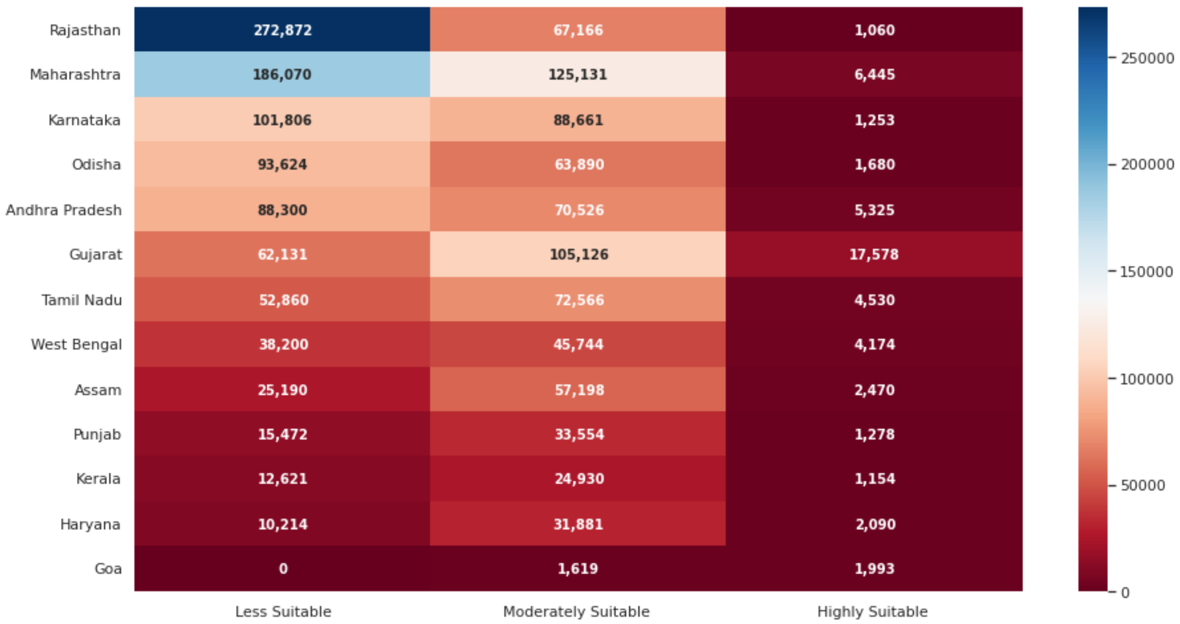

Figure 6: State-wise land suitability for hydrogen valleys (in km^2)

The parcels of land (see Figure *6*) are graded as highly suitable, moderately suitable, and least suitable for H_2 valleys, and Gujarat has the largest parcel of most suitable land (17,578 km^2), followed by Maharashtra (6,445 km^2) and Andhra Pradesh (5,325 km^2). To further expand the purview of the suitability of land, the major chunk of moderately suitable land is available in Maharashtra (125,131 km^2), Gujarat (105,126 km^2), and Karnataka (88,661 km^2).

Electricity is identified as a key performance indicator in electrolysis. This electricity demand is to be met by renewable energy to meet green hydrogen requirements. Since most of the states shortlisted in AHP are amenable to solar power, it is assumed that decentralised solar power will be used as the mode of generation of electricity. Wind power, though not factored in the present work, will be evaluated in the subsequent analysis. Typically, around 50 kWh of electricity is required to produce 1 kg of green hydrogen. This number is expected to change depending on the efficiency and operating parameters of electrolysers (Andi Mehmeti G. A., 2018).

To quantify the size of the plot required for generating electricity from decentralised solar systems, it is assumed from Ministry of New and Renewable Energy (MNRE) estimates that a solar plant covering an area of 5 acres can generate 1 MW (MNRE, 2019) and receive 6 hours of peak solar irradiance for 253 to 327 days a year depending on its geographical location (Pulak Guhathakurta, 2020; India Meteorological Department, 2020). By virtue of Gujarat accounting for nearly 40% of the hydrogen demand among all the valleys, resource requirements are skewed towards the state.

Water requirement is another important indicator to gauge a state's capacity to house a hydrogen hub. It is computed based on the available literature, and an empirical correlation is identified as 9 kg of feed water required per kg of hydrogen (Andi Mehmeti, 2018). This water demand is to be met from freshwater available in the respective states. Alternative sources of water include the deionisation of ocean water using specialised desalination units.

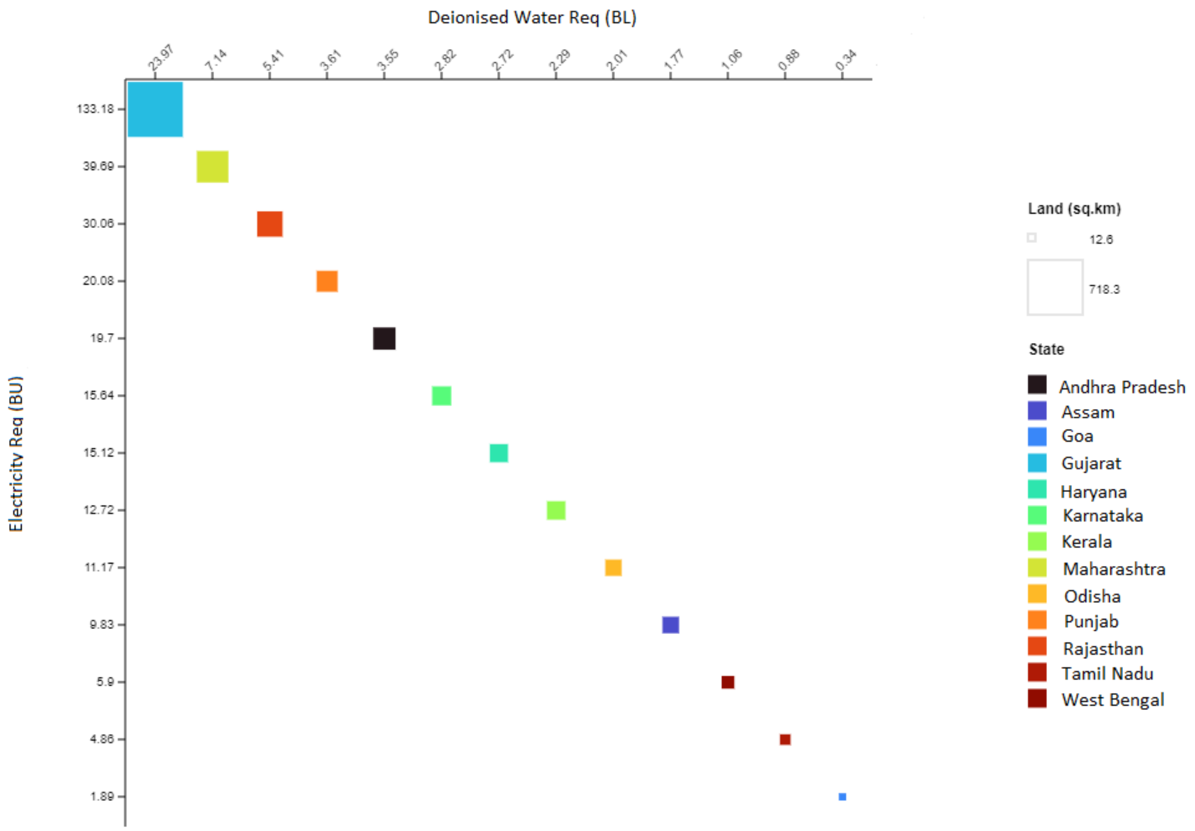

Figure 7: Key performance indicators

Way Forward

Hydrogen can be used as both feedstock and fuel. Regardless of its use, it is expected to provide a sustainable cushion as India aims to substitute fossil-fuel-based energy needs. Currently, refineries and fertilisers are utilising hydrogen in their utilities. Enhancements in demand diversification will be governed by industries (steel and cement), transport (freight segment), and city gas distribution (blended gas) networks. Green hydrogen is expected to be a game changer in countries that are reliant on fossil fuels. However, to produce green hydrogen, renewable energy and water availability will be key.

Electrolyser manufacturing capability is going to determine the progress of green hydrogen production. Assuming that the needs around electrolysers are met, the results from this study will provide a basis for governments and investors to consolidate their opinions on H_2 valleys. Valleys of this scale will propel India as a global leader in the hydrogen sector. In due course of time, India can also start exploring possibilities of exporting hydrogen to Asia-Pacific partners.

We will continue to work on revising criteria using suggestions from stakeholders, and current results are expected to get refined. Preliminary results from AHP will be helpful in developing a full-fledged computational tool, which will act as an atlas (the H_2 Atlas developed by CSTEP) for interested stakeholders. This tool can be used to identify suitable land for setting up hydrogen production units from where hydrogen will be shipped to demand centres.

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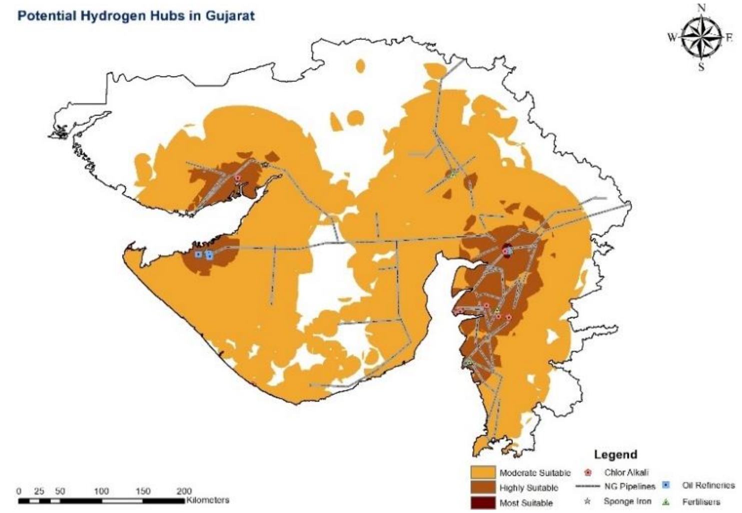
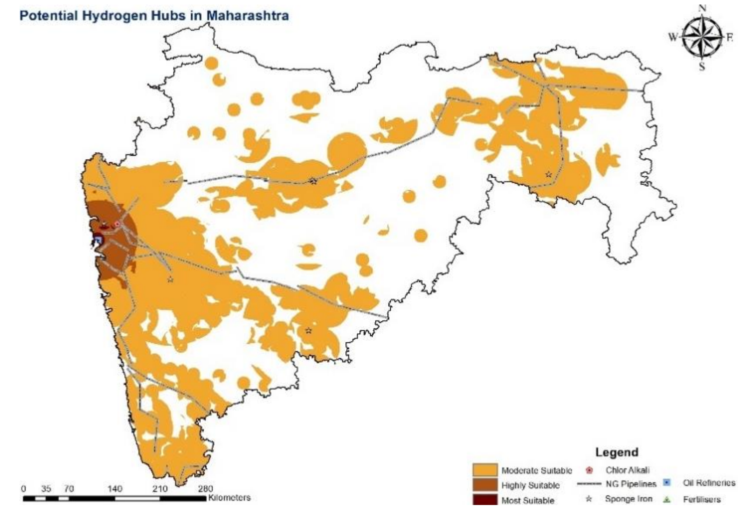
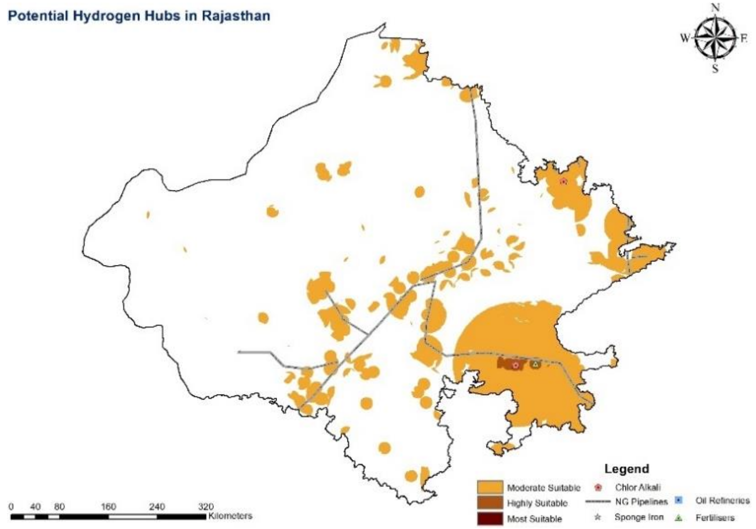
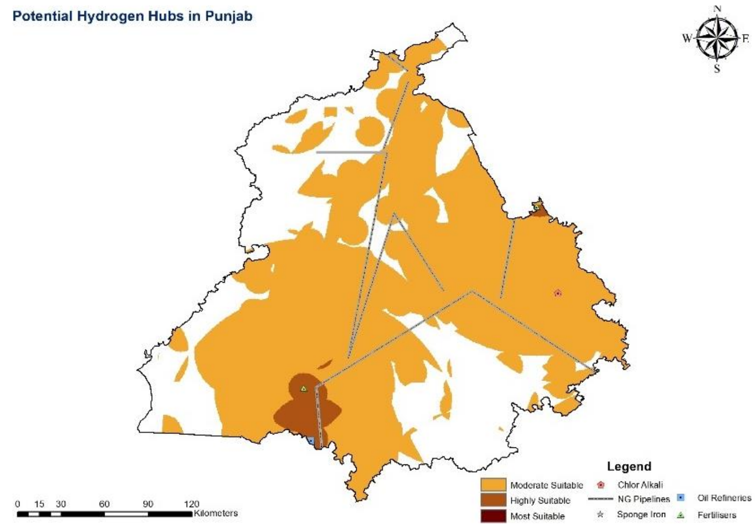
Appendix I

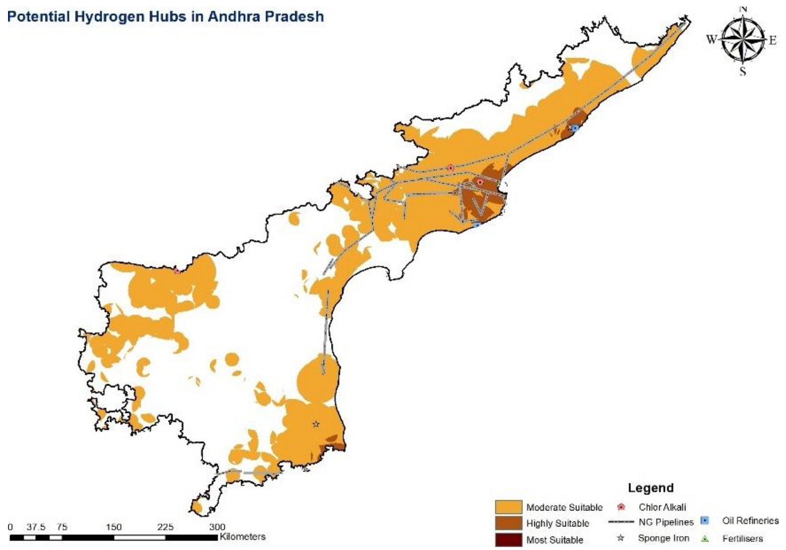
State-Wise Potential of Hydrogen Valleys

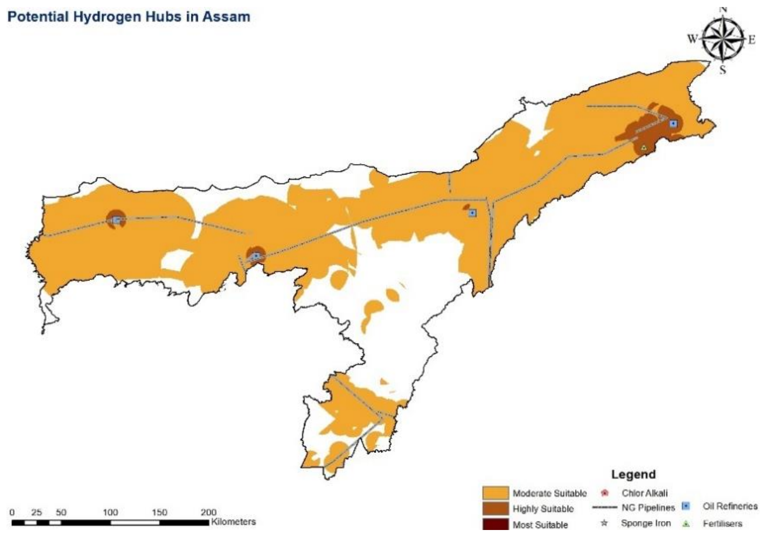


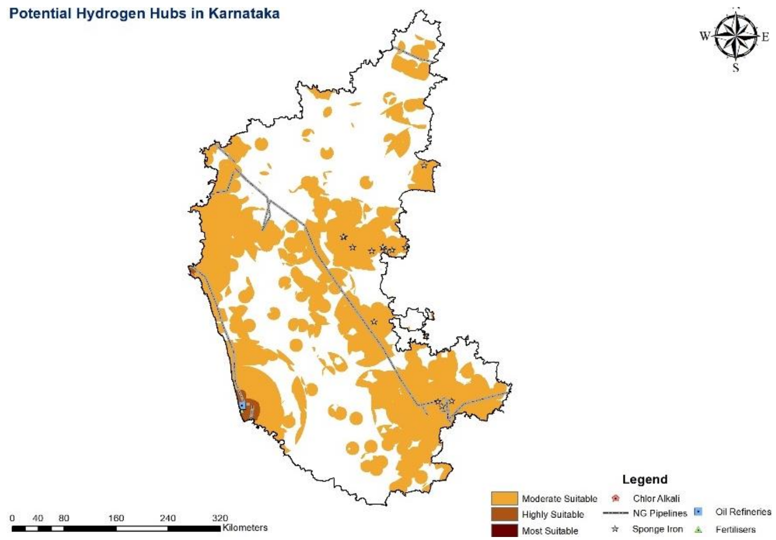


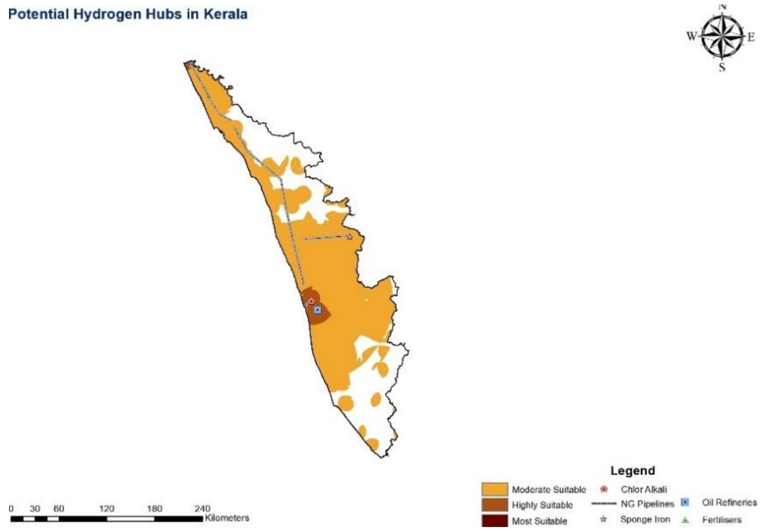


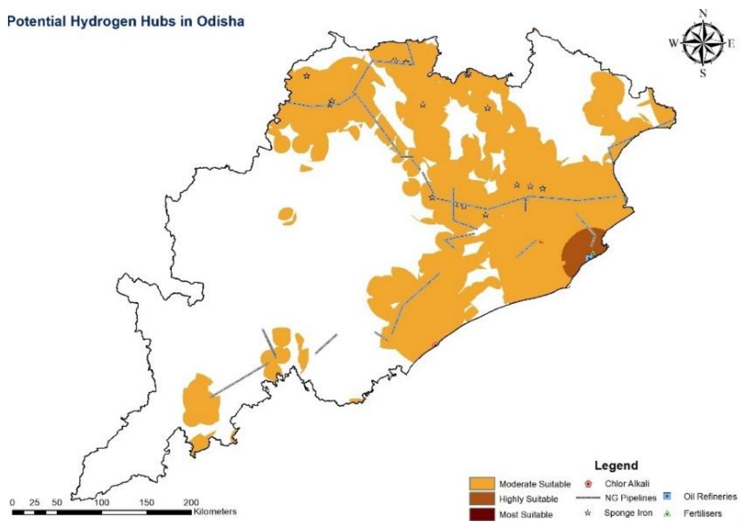


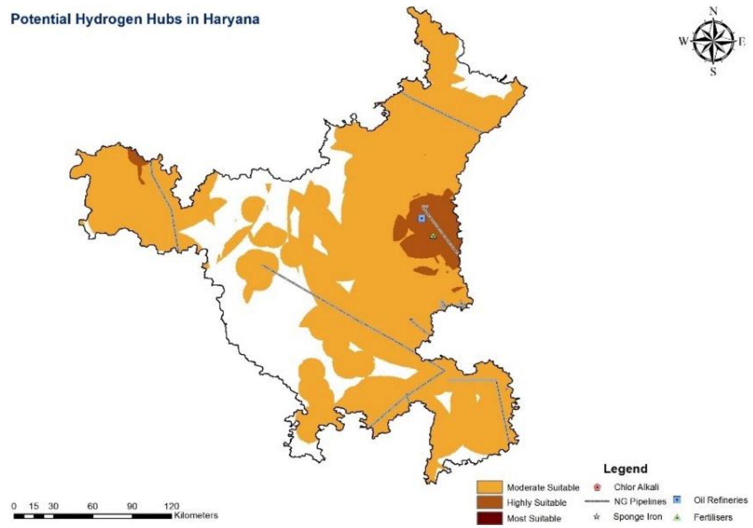

Potential Hydrogen Hubs in Andhra Pradesh
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 37.5 75 150 225 300
Kilometers

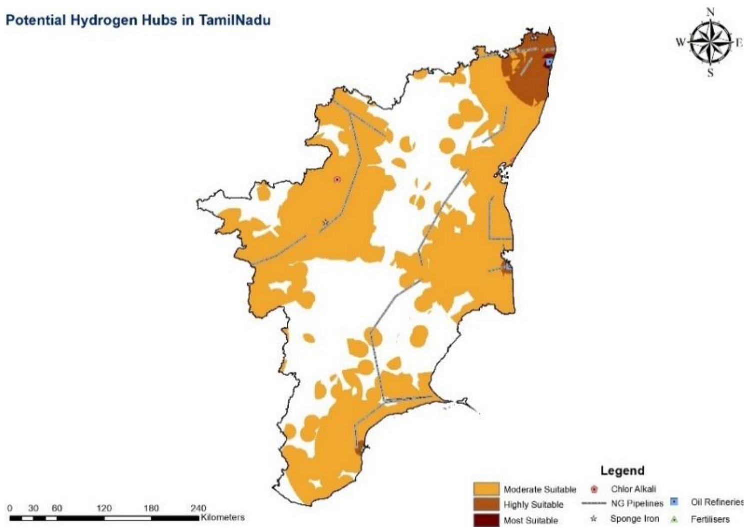

Potential Hydrogen Hubs in Assam
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 25 50 100 150 200
Kilometers

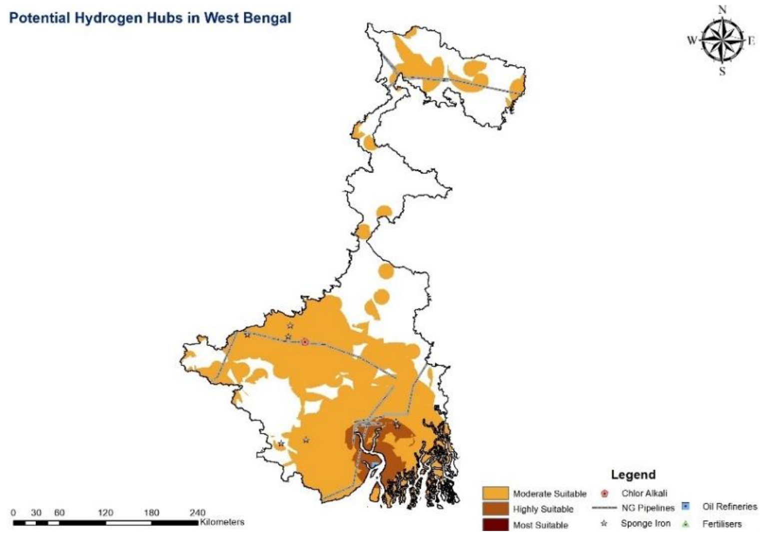

Potential Hydrogen Hubs in Karnataka
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 40 80 160 240 320
Kilometers


Potential Hydrogen Hubs in Kerala
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 30 60 120 180 240
Kilometers


Potential Hydrogen Hubs in Odisha
N
W
E
S
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 25 50 100 150 200
Kilometers


Potential Hydrogen Hubs in Haryana
N
W
E
S
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 15 30 60 90 120
Kilometers


Potential Hydrogen Hubs in TamilNadu
N
W
E
S
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 30 60 120 180 240
Kilometers


Potential Hydrogen Hubs in West Bengal
N
W
E
S
Legend
Moderate Suitable
Highly Suitable
Most Suitable
Chlor Alkali
NG Pipelines
Sponge Iron
Oil Refineries
Fertilisers
0 30 60 120 180 240
Kilometers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