Optimal Dynamic Strategy of Building a Hydrogen Infrastructure in Beijing

Zhenhong Lin, zlin@ucdavis.edu
Dr. Joan Ogden, jmogden@ucdavis.edu
Dr. Yueyue Fan, yyfan@ucdavis.edu
Dr. Dan Sperling, dsperling@ucdavis.edu
Institute of Transportation Studies, University of California, Davis
The United States

Abstract

This paper describes the on-going Hydrogen Infrastructure Transition (HIT) modeling efforts with the Beijing case study. HIT uses dynamic programming to generate optimal decisions on when, where, at what sizes and by what technologies to build up a regional hydrogen infrastructure while minimizing the discounted value of facility cost, environmental disbenefit and travel time disbenefit.

In the case study, we use the 380-kilometer Beijing urban expressway network for spatial representation and 2010~2060 as the transition study period. We relied on Beijing Master Plan, demographic projection and traffic data in estimating spatial distribution and temporal growth of hydrogen demand. Gaseous fueling station, natural gas steam reforming onsite, water electrolysis onsite, water electrolysis central plant, coal gasification central plant (with and without carbon dioxide sequestration), tanker truck and pipeline are identified as the 8 potential technologies to be selected by the optimization algorithm. The dynamic optimization algorithm of the HIT model incorporates station citing and sizing, pipeline length and flowrate, station module expansion, onsite-to-refueling-only switch, sequestration upgrade, technology evolvement, and availability of by-product hydrogen.

Based on the data assumption, we find that $2.5 billion (in 2010 worth) is the minimum cost for Beijing to transition to an equilibrium hydrogen infrastructure of 2 coal gasification plants, 350km pipeline and 100 refueling stations. The revenues can breakeven all the costs if hydrogen is charged to the consumers at $2.15/kgH2 from 2010 to 2060 and $0.95/kgH2 after 2060.

1. INTRODUCTION

Hydrogen as an alternative transportation fuel offers the prospects of reducing pollution, greenhouse gases, and oil use. To develop a hydrogen economy, it is necessary to estimate the costs of building up the hydrogen infrastructure. One popular estimation approach is using a simplified city model to estimate facility sizes and numbers as inputs for scenario analysis. This type of estimation is useful for nation scale or general analysis, but very limited in regional analysis, where considerations on road network, resources availability, land use pattern, and so on, become necessary. Another issue is dynamics and optimization. From the policy making perspective, it is important to know the minimum total discounted cost of transition to a stable hydrogen infrastructure and the financial implication of the optimal transition for private investors. As far as we know, there has not been much effort on investigating dynamic transition using optimization technique in the field of hydrogen analysis.

Building a hydrogen infrastructure including production, transportation, and refueling facilities is an evolutionary process. This process might start from small-scale facilities refueling stations with on-site production and end up with a widespread infrastructure based on central production and pipeline. The infrastructure investment strategy depends on and is linked to market development strategies. Likewise, on the supply side, regional spatial and economic features, such as easy availability of hydrogen from refineries and chemical industries, land use patterns and travel behavior (affecting location of refueling stations and therefore hydrogen distribution costs), could lead to different infrastructure investment strategies. All these factors, as well as facility costs, are relevant in determining the minimum cost and optimal transition decisions. The choices are so complex and so numerous that straightforward calculations are not feasible. To tackle this kind of problem, the Hydrogen Infrastructure Transition (HIT), a dynamic programming-based optimization model, was recently developed.

In this paper, we first introduce the HIT model in terms of problem formulation, methodology framework and modeling assumption. Then the Data section presents the data assumptions used for the urban Beijing case study. Results and Findings section shows the outputs from the HIT model and some observations. A brief summary of this paper is also provided.

2. METHODOLOGY

2.1. Problem Statement

The problem of any model must be clearly and concisely stated before any further methodology discussion. The problem tackled by HIT model is how to minimize the costs of a regional transition to a hydrogen infrastructure for transportation. For each time period, the total refueling capacity must meet or exceed the projected demand. To model the trade-off between facility cost and consumer refueling convenience, the monetary cost of refueling travel time is incorporated. To model the trade off between facility cost and environmental cost, the monetary damage cost of carbon dioxide (CO_2) in dollar per ton carbon is incorporated. To model the transition dynamics, technology evolvement and growth of

demand are taken into account.

We developed the HIT model to aid solving the problem stated above. The main technique of HIT model is dynamic programming. The guiding framework for the HIT model is Principal of Optimality: an optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state as the same as the one resulting from the first decision (Bellman, 1957).

This leads to the following general model framework:

$$MPW_t = \min_{X_t}\{TC_t + SC_{t+1} + MPW_{t+1}\}$$

$$MPW_T = SV(X_T)$$

Where :

MPW_t : the minimum cost from stage t to stage T (transition study period);

TC_t : transition cost or marginal capital cost from stage t to $t+1$;

SC_{t+1} : stage cost or operating cost of stage $t+1$.

X_t : decision variables at stage t on where, when, what sizes/how many, by which technology.

$SV(X_T)$: salvage value of the end configuration X_T.

HIT model accounts for the spatial aspect of the hydrogen infrastructure by using a road network to represent the region of interest. Each intersection node on the network is attributed with a hydrogen demand quantity, which is calculated based on vehicle-mile traveled by the vehicles heading for the node. For any given configuration of refueling stations on the network, the total travel time cost can be calculated by assuming each of these hydrogen demand quantities is served by the nearest refueling station. Thus, the locations of any given number of refueling stations can be optimized so that the total travel time cost is minimized. In the HIT model, multiple refueling stations at the same node also help reduce travel time, which is realistic and called "node-wide siting", as opposed to "network-wide siting". By integrating both node-wide siting and network-wide siting, the HIT model can allocate more than one station to the busy node (with large accumulated hydrogen demand) with some other nodes still empty, i.e. multiple-station nodes occur before at least one station is built at every node.

3. DATA

3.1. Facility Cost Data Source

We derive the cost data, using cost-capacity method, all from (NAS, 2005), except that the delivery distances of pipeline and tanker truck are determined by the HIT model based on the real spatial road network. That is, for example, we implicitly use U.S. grid mix and U.S. labor to calculate operating cost, and we assume all the technologies are available for Beijing at the (NAS, 2005) cost level. We make these assumptions due to lack of better data. One possible improvement on these assumptions is using location factor to adjust the cost data between the U.S. and China, which might be addressed in further research.

3.2. Study Period and Time Step

The transition study period is from 2010 to 2060. Time step is 5 years, so there are 11 stages with 2010 as the first stage and 2060 as the last stage. According to the convention of engineering economics, capital cost is charged at the beginning of stage, while any other type of cost is charged at the end of stage.

3.3. Facility Options

The facility options are listed in Table 1. The code name is defined for convenience of plotting and explanation.

Table 1: Urban Beijing Case Facility Options

Facility Technology	Assumption	Code Name
gaseous hydrogen refueling station, 2,740 kg H2/day/station, 20 station per decision step	Refueling-only capability; supplied by pipeline from central station or tanker truck from by-product hydrogen supplier	Fb
expansion module for Fb, 2,740 kg H2/day/station, 20 station per decision step	Same as above; added to an existing Fb station to expand refueling capacity	Fm
distributed onsite station via steam reforming of natural gas, 2,740 kg H2/day/station, 20 station per decision step	Have both refueling and production capability; self-sustained; can be converted into gaseous refueling station Fb	PFb-NG
expansion module for PFb-NG, 2,740 kg H2/day/station, 20 station per decision step	Same as above; can be converted into Fm	PFm-NG
distributed onsite station via electrolysis of water	Have both refueling and production capability; self-sustained; can be converted into gaseous refueling station Fb	PFb-Elec
expansion module for PFb-Elec, 2,740 kg H2/day/station, 20 station per decision step	Same as above; can be converted into Fm	PFm-Elec
central plant via coal gasification with CO2 capture, 1,500,000 kg H2/day/station, 1 station per decision step	Supply hydrogen via pipeline to Fb and Fm	Pb-coal-seq
central plant via coal gasification, 1,500,000 kg H2/day/station, 1 station per decision step	Same as above; can be upgraded to Pb-coal-seq	Pb-coal
central plant via electrolysis of water, 100,000 kg H2/day/station, 1 station per decision step		Pb-Elec
pipeline for gaseous hydrogen distribution, varied flow rate, continuous length		PL
tanker truck for liquid hydrogen distribution, continuous workload		TK

3.4. Facility Costs

We use cost-capacity method to derive cost data for the facility options on Table 1 from (NAS, 2005). We assume the current technology estimation for year 2005 and the future optimism technology estimation for year 2060, then we interpolate for cost estimation for year 2010 through 2055 in the quadratic manner.

Facility costs in 2005 and other year costs as fraction of respective 2005 costs are shown in Figure 1. Note the denotation here: CC for capital cost in million $ (m$), FC for fixed cost (including fixed operating cost and non-fuel O&M) in m$ per year (m$/yr), and VC for feedstock variable cost in m$/yr. Combining the denotation in Table 1, PFm-Elec VC as an example stands for the annual variable cost for one onsite expansion unit electrolysis of water.

Figure 1: Facility Cost over Time as Fraction of the 2005 cost
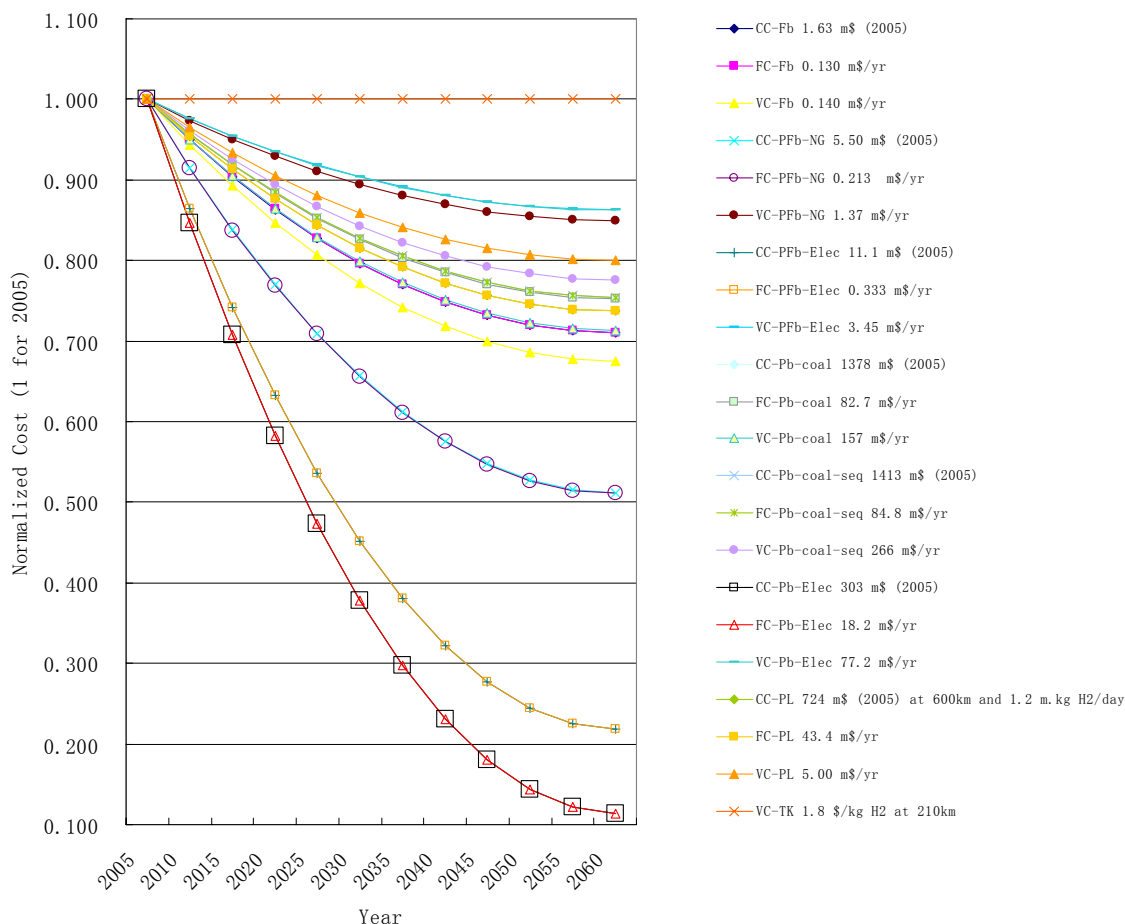
Also note the cost estimation for pipeline assumes 600km delivery distance and 1.2 million kg H2/day flow rate, as assumed by (NAS, 2005). We treat the estimation as a reference case to estimate pipeline cost based on real distance for Beijing and real flowrate (flowrate might be significantly small for some downstream pipeline segments). The tanker truck cost estimation from (NAS, 2005) is for a delivery distance of 210km. The 1.8 $/kg H2 estimation is used as a reference case for real delivery distance consideration in the urban Beijing case. Tanker truck service is in form of rental or contract service, so no capital and fixed cost is considered.

Cost data for expansion modules are not shown. Cost data for expansion modules are similar to those for base stations, except that the capital cost is smaller (no need to purchase

the land again, for example).

When normalized, fixed cost data are very close to capital cost data and the curves overlap, because fixed cost are estimated as a certain percentage of capital cost.

3.5. Road Network and Traffic

The urban expressway network of Beijing is identified as the representative spatial network of urban Beijing, as the network serves 70%~80% of total motor vehicle traffic in urban Beijing. Beijing urban expressway network consists of 4 ring roads and 15 rapid connecting roads (4 of the 15 rapid connecting roads are still under construction). Due to lack of GIS data, distance of each road segment is measured by hand from commercial electronic map. Traffic count data are borrowed from literature (Li 2004) and personal communication.

3.6. Demand Projection

VKT (vehicle kilometer traveled) projection of 6 types of vehicles and distribution over the network are then modeled based on Beijing Master Plan (2004~2020), Beijing Transportation Development Outline (2004~2020), and population projection from Beijing Municipal Commission of Population and Family Planning. Second, the VKT distribution and projection are used to project FCV VKT distribution over time, optimize station locations and sizes, and optimize pipeline buildup process. Considering the Olympics event and the GEF Fuel Cell Bus Demonstration Project in Beijing, we estimate 18,300 fuel cell taxis and 2000 fuel cell buses in 2010 in Beijing and 80.39 ton H2/day (estimated 411 km/day for one taxi and 151 km/day for one bus) of hydrogen demand. This drives the hydrogen build-up process and therefore the private FCV penetration starting from year 2015. The demand for hydrogen over time is estimated as in Figure 2.

Figure 2: Vehicle Stock and Hydrogen Demand Projection for Urban Beijing Case
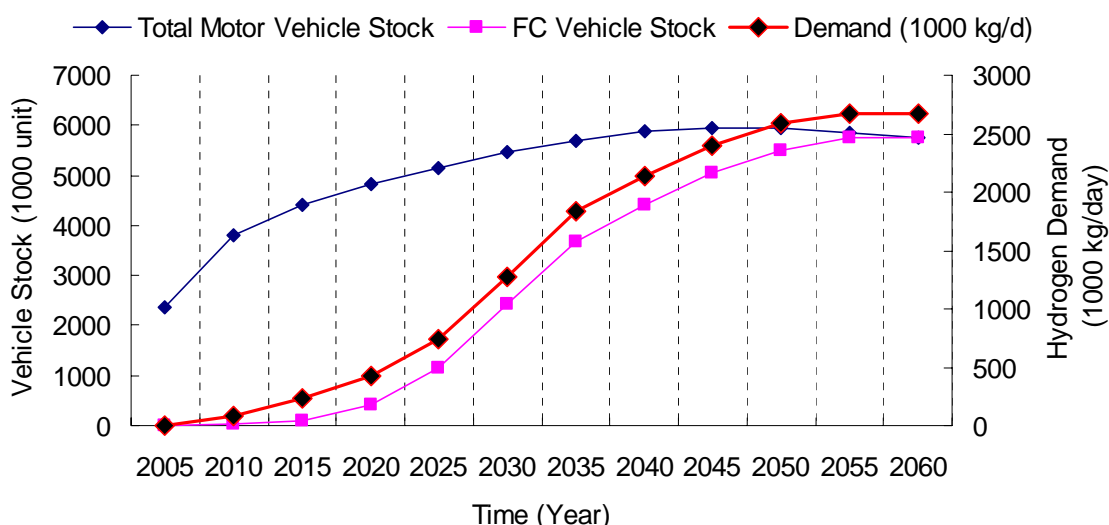
3.7. CO2 Tax

The use of CO_2 tax is intended to reflect the competition between coal (with CO2

sequestration and with CO2 sequestration), electrolysis, and natural gas reforming as hydrogen production technologies, as they have different well-to-pump CO2 emission factor. CO2 emission factor for these technologies are borrowed from the NAS report and plotted together assumed carbon tax on Figure 3.

Figure 3: CO2 Emission Factors and Carbon Tax over Time
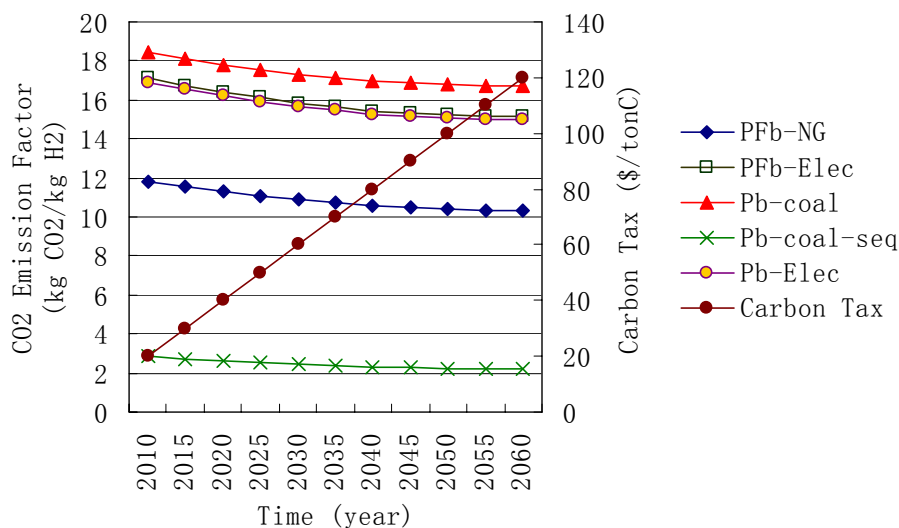
3.8. Refueling Station Location Optimization

The locations of refueling stations are optimized, assuming that consumers will choose the nearest stations and the possibility of need for refueling is determined by the traffic density along the network. Based on traffic data and the optimization algorithm, the relationship between refueling station number and the average travel time can be found, as shown in Figure 4.

Figure 4: Average Travel Time vs the Number of Refueling Stations with Location Optimized for Urban Beijing Case
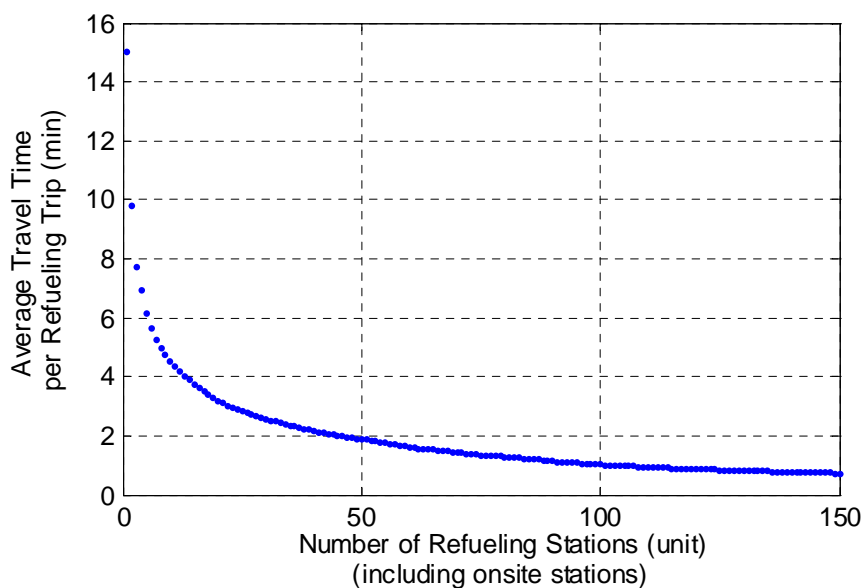
3.9.   Value of Travel Time

We use the exponential function to estimate monetary value of refueling travel time, as shown in Figure 5. The basic idea is 1) the value of refueling travel time is zero when the travel time is zero, i.e. when refueling stations are built everywhere, consumers don't mind spending a little more refueling travel time; 2) At some level of acceptable refueling travel time (2 min in this case study), the time value is half of the hourly rate (it is better to use Beijing average hourly rate other than the U.S. hourly rate used in this case study); 3) after the acceptable level, the time value increases rapidly. Ideally, survey should be conducted to determine the parameters of the exponential function or even the function structure.

Figure 5: Monetary Value of Refueling Travel Time
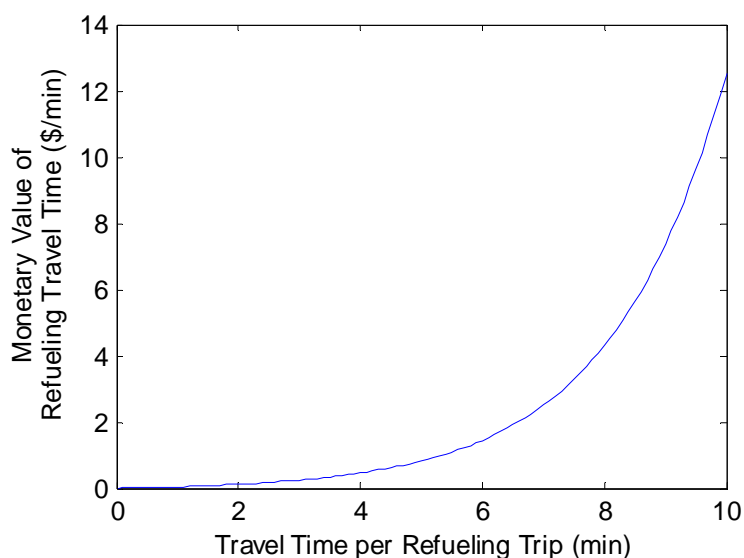

4.   RESULTS AND FINDINGS
4.1.   The optimal decisions

Table 2: Optimal Transition Decisions for Base Case: Urban Beijing Case Study

Facility	Fb	Fm	PFb-NG	PFm-NG	PFb-Elec	PFm-Elec	Pb-coal	Pb-coal-seq	Pb-Elec
2005	0	0	0	0	0	0	0	0	0
2010	0	0	20	20	0	0	0	0	0
2015	0	0	20	80	0	0	0	0	0
2020	0	0	20	140	0	0	0	0	0
2025	0	0	40	240	0	0	0	0	0
2030	60	420	0	0	0	0	0	1	0
2035	80	480	20	120	0	0	0	1	0
2040	100	700	0	0	0	0	0	2	0
2045	100	800	0	0	0	0	0	2	0
2050	100	880	0	0	0	0	0	2	0
2055	100	900	0	0	0	0	0	2	0
2060	100	900	0	0	0	0	0	2	0

The optimal decisions over time are generated by HIT model and showed on Table 2. We can observe that the transition starts from natural gas onsite production and evolve into the study-period-end configuration (see Figure 6) consists of 100 gaseous refueling stations, 2 coal gasification central plants with CO_2 sequestration, and 349 km pipeline. 40 onsite natural gas stations are converted into refueling stations in 2030 and interestingly, 20 onsite natural gas based stations are added and operated just for the stage 2035~2040 and converted in 2040 when another central plant is built. The model says it makes more economic sense to delay the second central plant construction by having some onsite stations temporarily satisfy the incremental demand. Central production begins in 2030. Once built, the central plant is of CO_2 sequestration capability.

Figure 6: Optimal Equilibrium Hydrogen Infrastructure Configuration (2060) for Urban Beijing Case Study
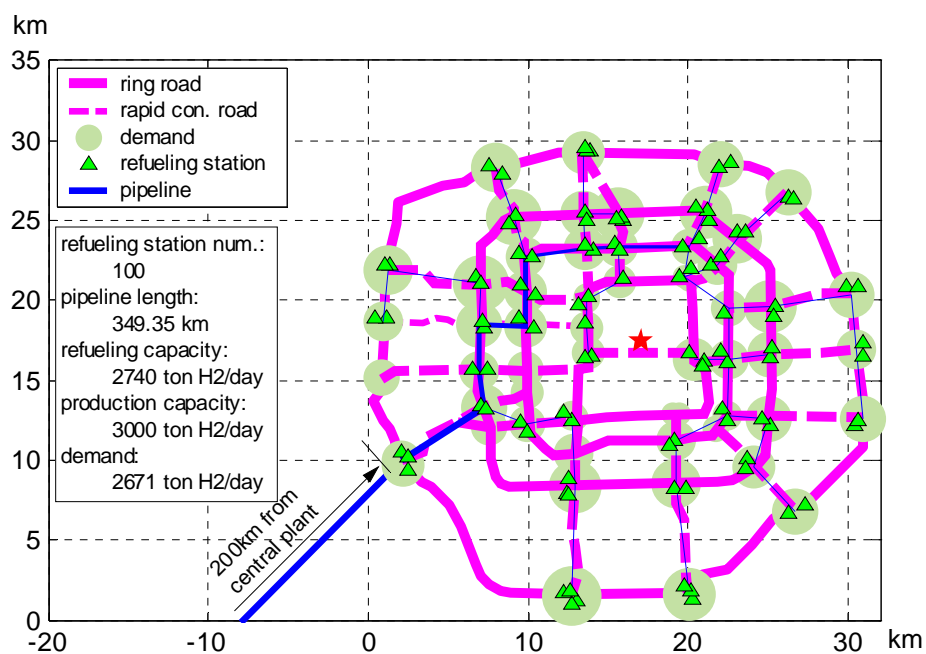
4.2. The overall cash flows

The cash flows during the transition study period is plotted in Fig 7, which can be used together with Table 2 to understand the optimal transition process. The total present worth (at year 2010 value) of infrastructure buildup and operation costs over infinite time horizon is $2,528 million. The present worth of transition buildup and operating costs from 2010 to 2060 is $2,501 million. The present worth of the cost of the equilibrium configuration after year 2060 is $25.58 million (discounted to 2010 from actual cash flow $922 million $/yr).

It should be noted that the time period is 5 years and a 12% discount rate is adopted. So non-capital cost data on the figure should be divided by 6.3528 (=(1+0.12)^5-1) to get the annual data. This manipulation is not applicable for capital cost, which is a one-time charge.

For clarification, "station" in Figure 7 includes refueling, onsite and central plant; so

station CC stands for capital cost on building refueling stations, onsite stations and central plants. Truck VC is the cost on renting tanker trucks to transport hydrogen. H2 purchase cost is that on buying by-product or interregional hydrogen at the factory price. Accessibility cost is the sum of time cost on refueling travel.

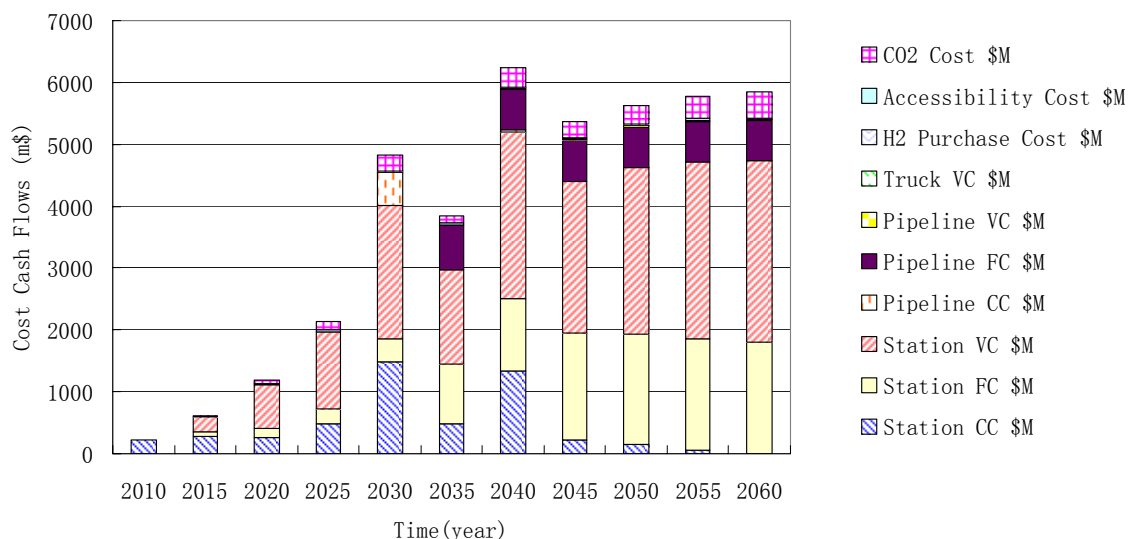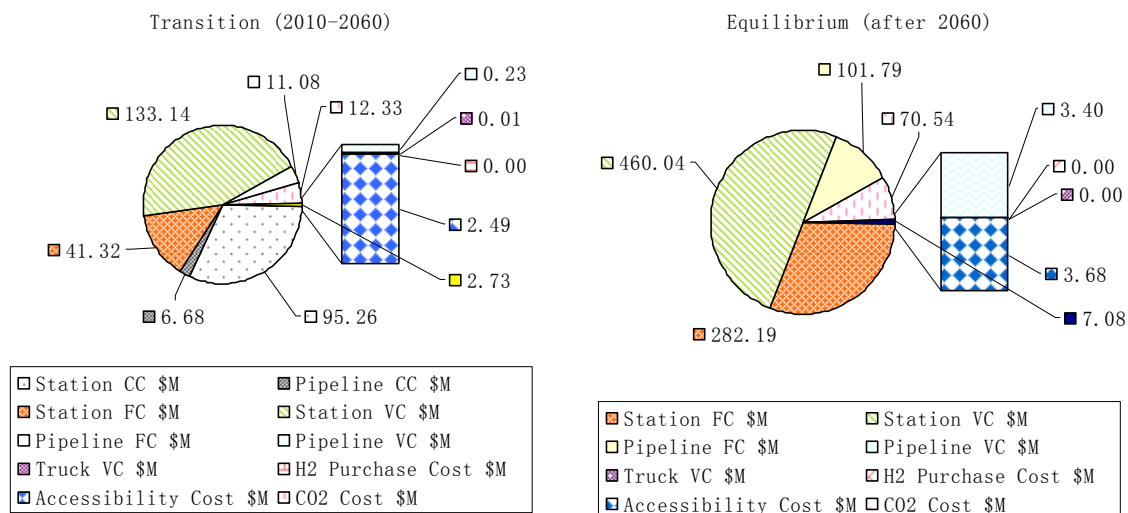Figure 7: Cost Cash Flows of Optimal Transition for Urban Beijing Case Study

Figure 8: Annualized Cost Component for Urban Beijing Case Study

4.3. Annualized Cost Distribution

It is interesting to see the relative magnitude of different cost components. One measurement is the annualized equivalent worth for each cost component. The annualized cost distribution is shown on Figure 8 to see the relative cost magnitude in the optimal transition process and the resulting equilibrium design. One should be careful not to use the
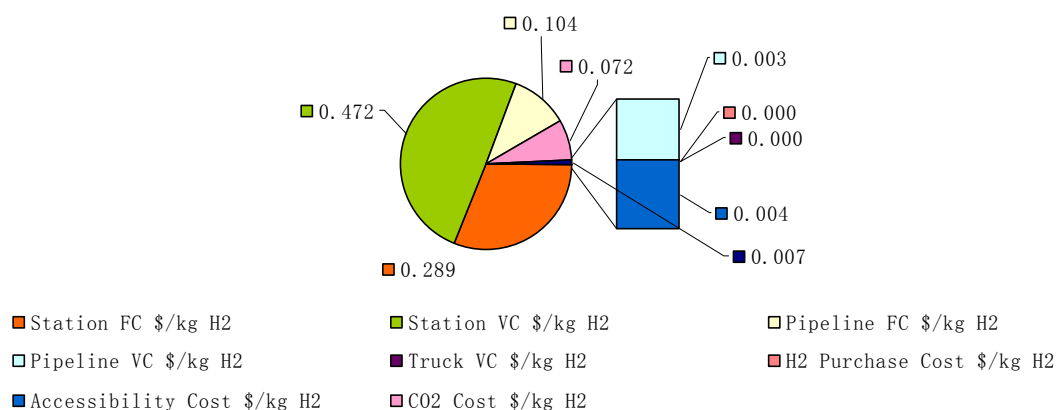
relative magnitude to judge on the relative importance of factors. In fact, since the dynamic transition is optimized, it is theoretically not economically feasible to reduce station cost by increasing accessibility cost, even though the accessibility cost seems so low. There are many issues intertwining, such as nonlinearity of time value, discreteness of facility size, cost estimation accuracy, and elasticity between cost components.

4.4. The constant breakeven hydrogen price

A breakeven hydrogen price is one that results in the same present worth of revenues as that of costs. For simplicity, we only look at two constant breakeven prices, one for transition period (2010-2060) and the other for equilibrium period (after 2060). For this case study, the constant transition breakeven price is \$2.15/kg H2. And the equilibrium breakeven price is \$0.95/kg H2. In other words, if hydrogen is priced at \$2.15/kg H2 from 2010 to 2059 and at \$0.95/kg H2 from 2060 on, the rate of return at 12% per year is just realized.

It is interesting that the equilibrium breakeven price is much lower than the \$1.64/kg H2 in (NAS, 2005). From Figure 9, production and dispensing costs amount to 0.78 \$/kgH2, as opposed to 1.06 \$/kgH2 in (NAS, 2005). One reason is that the 1000 refueling station modules (2,740 kg/day each, same as in the NAS report) occupy only 100 pieces of land to form 100 big refueling stations. This greatly reduces costs on general facilities, engineering permitting & startup, contingencies, and working capital, land & misc. This is just the optimized result of trading off between travel time cost and refueling station cost. Another reason is that we evaluate bigger coal central plant, 1.5 million ton H2/day as opposed to 1.2 million ton H2/day in the NAS report, which also lowers cost due to scale of economy. And distribution (only pipeline in the equilibrium design) accounts for \$0.075/kgH2, much lower than \$0.31/kgH2 in (NAS, 2005). As discussed before, the length of pipeline is about 350km for the Beijing case, much shorter than the 600km assumption in the NAS report. And from Figure 6, we see that the pipeline flowrate varies from upstream to downstream, as opposed to the constant 1.2 million ton H2/day flowrate assumption in the NAS report. Optimized length and flowrate reduce the distribution cost per kg H2.

Figure 9: After-2060 Equilibrium Hydrogen Breakeven Price for Urban Beijing Case Study

Legend:
- Station FC \$/kg H2
- Station VC \$/kg H2
- Pipeline FC \$/kg H2
- Pipeline VC \$/kg H2
- Truck VC \$/kg H2
- H2 Purchase Cost \$/kg H2
- Accessibility Cost \$/kg H2
- CO2 Cost \$/kg H2

Values: 0.104, 0.072, 0.003, 0.472, 0.000, 0.000, 0.004, 0.289, 0.007

4.5. More on Hydrogen Pricing

From the investor perspective, one question is how to breakeven the costs sooner by charging more on hydrogen sold to consumer while maintaining the 12% rate of return. This question is also of interest to public policy making, because it is desirable to find a pricing scenario attractive to both consumers and private investors. Figure 10 show the different hydrogen pricing scenarios. The Y-axis value is the ratio of the cumulative revenue (converted to equivalent 2010 value) to the cumulative cost, so the breakeven time point is when the revenue ratio curve crosses the cost ratio horizontal line. We can see that the breakeven point can be as early as 2020 if the $3.50/kgH2 pricing scenario is adopted. This can be a very interesting finding, if all the assumptions are applicable enough for Urban Beijing.

Figure 10: Hydrogen Pricing Scenarios for Urban Beijing Case Study
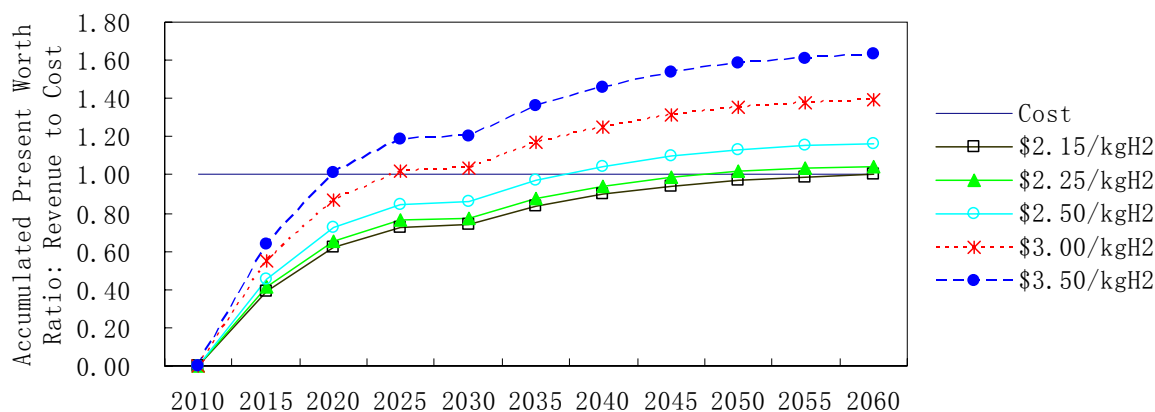
5. SUMMARY

In this paper, we introduce the newly developed HIT model and present the results of its application in the urban Beijing case study. The main inputs include estimated demand over time, spatial road network, traffic flow distribution, regional by-product hydrogen availability, spatial distance of coal resource, and technology cost estimation derived from (NAS, 2005). The major output is the optimal decision series to build up the hydrogen infrastructure in urban Beijing. Based on the data assumptions (which certainly need more investigation to enable more reliable conclusions), we find that $2.5 billion is the minimum cost for Beijing to transition to an equilibrium hydrogen infrastructure of 2 coal gasification plants, 350km pipeline and 100 refueling stations. The revenues can breakeven all the costs if hydrogen is charged to the consumers at $2.15/kgH2 from 2010 to 2060 and $0.95/kgH2 after 2060. The breakeven time point can be as early as 2020 if hydrogen is priced at $3.50/kgH2.

We believe the data assumptions in this case study should be further investigated so that reliable conclusions can be made. Yet, we believe an optimal dynamic design of the transition decisions can lead to findings significantly more reliable and different from those based on static (as opposed to dynamic) and average (as opposed to regional) data assumptions.

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