MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Analyze Technology Options in Electric Vehicle Infrastructure

ESD.71 Engineering System Analysis for Design

David Diaz Dominguez

12/8/2009

Table of contents

Analyze Technology Options for EV Infrastructure

Abstract

This Application Portfolio analyzes the effect of using flexibility in the design of dedicated charging stations for Electric Vehicles to improve the NPV (Net Present Value) of the project when facing uncertainty in demand. A Fixed and a Flexible design are compared in two different set ups: a two stage analysis using decision analysis theory and a multi-state Lattice model with dynamic programming. In both set ups, the flexible design yields better outcomes.

Background

The concern about the environmental impact of automotive vehicle emissions as well as the increase in fossil fuel prices has boosted the development of Battery Electric Vehicles (BEV's). Automakers like Renault-Nissan, GM, Toyota and Ford have announced that BEV's will be important pieces in their portfolios in the near future. Also, most OEM automakers have shown at least a concept vehicle with this technology.

Current designs show that autonomy and cost will be the key factors to the success of this solution. Most of the full EV working prototypes have around 100 miles autonomy per charge, which seems to be good for short commutes and city driving duties. Other studies suggest that 80% of the potential EV owners will need to charge their vehicles more than once per day.

Governments are also concerned about sustainability and are fostering projects to develop technologies that are eco-friendly. In some countries, tax incentives were applied to vehicles that use alternative sources of energy and hybrids. It seems that governments would be supporters of the development of infrastructure for electric vehicles. In the industry side some companies have recognized the business opportunity of creating and managing EV infrastructure. Companies like Better Place or Coulomb Technologies have started to develop integral solutions for this network of charging stations. Deployment of EV infrastructure is expected to be in the form of home installations, parking lots, restaurants, hotels and dedicated stations.

System description

Business ecosystem

The most important players in the business ecosystem in the Electric Vehicle industry are:

- **EV Infrastructure Integrators** – Provide an integral service to the end user (EV owner) by managing a network of charging facilities at homes, public/private buildings and dedicated charging stations.
- **EV infrastructure manufacturers** – These companies have developed the technology to charge EV vehicles using different methods. Some of the products offered are: home charging stations, public charging stations and couplers.
- **Automotive OEM's** – In addition to producing EV's, this sector will be defining the charging standards (port configuration and methods) and selecting the battery technology. Also, Automotive OEM's will be defining the autonomy of the vehicle.
- **Battery Manufacturers** – The technology used in batteries will determine autonomy and charging speed.
- **Energy industry/Utilities** – It is likely that consumer adoption will depend on the cost of ownership of EV vehicles. The cost of electricity and its generation method (fossil fuels vs. renewable energy) will be important.
- **Government** – Through incentives, sponsorship and investment, the government can facilitate the adoption of EV vehicles. Government will be important in the deployment of charging infrastructure (in public facilities).
- **Other businesses that provide EV charging service** – Owners of hotels, restaurants, entertainment businesses and general employers are likely to offer the availability of charging stations to their customers and employees.

EV Charging Methods / Standards

In the United States, the NEC (National Electrical Code) Handbook considers 3 conductive charging types for Electric Vehicles:

- **Level I** – This charging level uses 120V AC, 12 A, and a single phase outlet (similar to home connections in the US). This level requires between 8-14 hours to fully charge a vehicle (depending on the battery technology and size).
- **Level II** – Use 208-240V AC, 32 A and a SAE J1772 connector. This level can fully charge a vehicle in a range of 3-6 hours.
- **Level III** – Also known as fast charging, this level use 480V AC, 400 A (some developments use DC). It is expected that this technology will fully charge a vehicle in around 20 minutes. Although there are some working prototypes, this charging level is not available now for EV infrastructure. It is expected this charging level will be available within the first 2 or 3 years of EV mass production.

In addition, because of the need of compatibility between infrastructure and EV's, Automotive OEM's are promoting the creation of standards in the interfaces (connectors and cables). In North America, SAE J1772 is the standard that homologates the specifications of the charging methods and is in advanced stage of development. GM, Ford, Chrysler, Nissan, Toyota Honda and Tesla are debating the final specs for this standard.

EV infrastructure system

The system under analysis is constituted by a network of charging stations managed by an IT system that provide the service of "refueling" the energy storage system of EV vehicles. Charging stations can be categorized in three groups per location:

1. **Home charging sites** – Technology to be used to charge the vehicle when the customer is at home. These charging units are expected to adopt Level I.
2. **Public and private building charging sites** – EV installations in parking lots, restaurants, hotels, work places, etc. These stations allow customers to charge their vehicles when they are working, shopping, etc. These sites are likely to adopt Level II.
3. **Dedicated charging sites** – These stations are analog to conventional gas stations and will be located in the main roads. These will allow customers to charge their vehicles while commuting.

Assuming the role of an **Integrator,** this project will focus on the third group of charging facilities: the Dedicated Charging sites. Considering the uncertainties that the industry will face in the upcoming years, this project will analyze the use of flexibility in the design of the dedicated charging sites.

Elements of uncertainty

- **Electric Vehicle sales**: This parameter will determine the demand for charging EV vehicles and is considered the most important uncertainty in this domain. As EV vehicles have not been mass produced yet, there is no historical data. The reference points available are projections to the future. This analysis considers that environmental concerns and three uncertain factors (oil price, electricity price and incentives) will affect the adoption of EV vehicles (that generate demand for charging):
    - ***Environmental concerns****:* EV's are seen as one of the alternatives to reduce the CO_2 footprint of personal transportation. If further studies demonstrate that the CO_2 footprint of EV's is smaller than future IC (internal combustion) vehicles, more people will be adopting these vehicles.
    - ***Price of oil****:* The adoption of EV's will be definitely affected by the cost of ownership relative to IC vehicles. Clearly, one of the factors that must be considered is the variation in the price of fossil fuels. The EIA has projected different scenarios for the price of oil in the upcoming years (see figure 1).

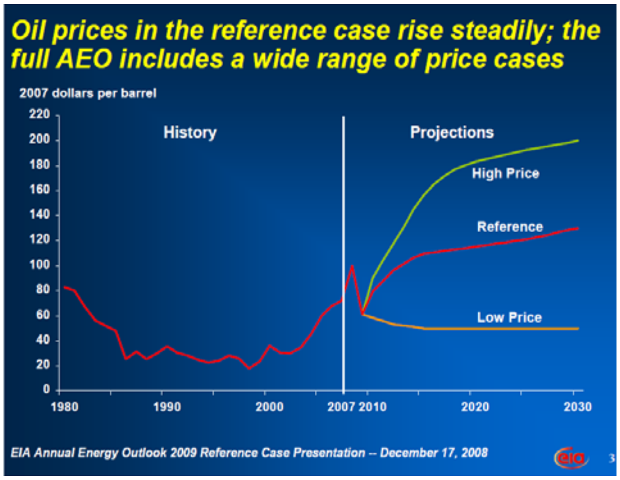


Figure 1. Forecast oil price (high, reference and low price) [2007 dollars per barrel]. Source: EAI Energy Outlook 2009 – Reference case presentation

electricity. The EIA has also a model that project different levels of price for the next years. (Figure 2).

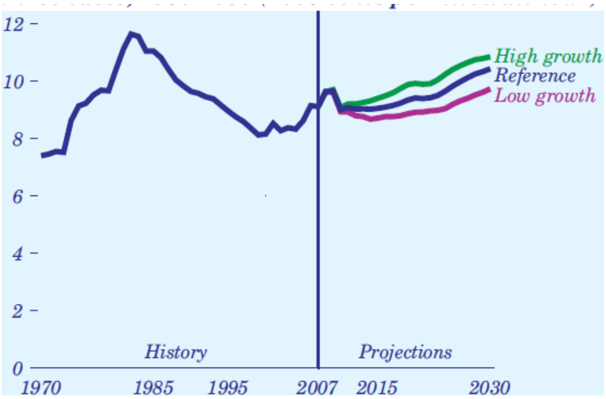


Figure 2. Average U.S. retail electricity prices (high, reference and low) [2007 cents per kW-hr]. Source: EAI Energy Outlook 2009

- **Incentives.** Incentives can play a major role to increase the demand for EV vehicles. These can be granted by the government or by the private sector. This analysis considers a scenario in which companies in the EV sector lease batteries to the user so the initial investment to purchase an EV vehicle is reduced.

To integrate these uncertainties, this project will use the model proposed by researchers from the University of Berkeley in the report: “Electric Vehicles in the United States, A New Model with Forecasts to 2030”. This model integrates the uncertainties described above with the expected number of vehicles to be sold in the United States in the next years. As result, this model suggests three different levels for the sales of EV vehicles: Baseline, high oil price and subsidized batteries. Figures 3 and 4 show the data used in this project:

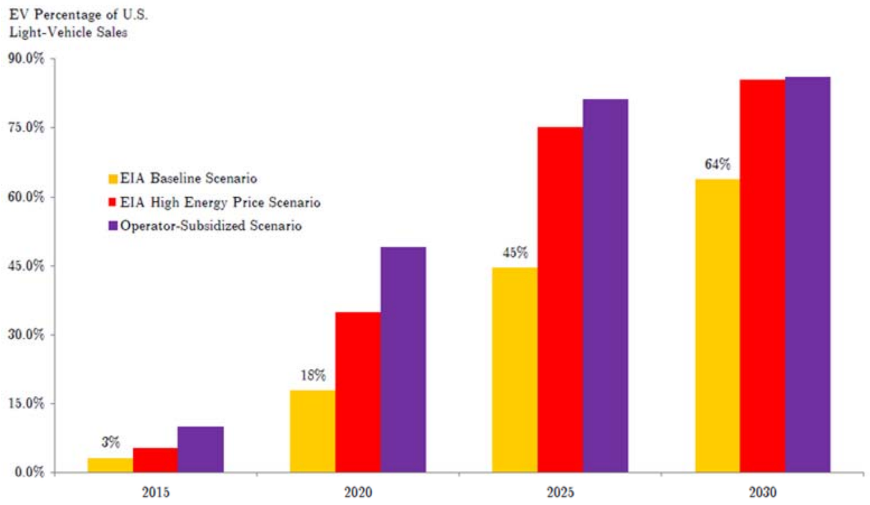


Figure 3. Three Scenarios for the U.S. Market Share of Electric Vehicles. UC Berkeley, 2009.

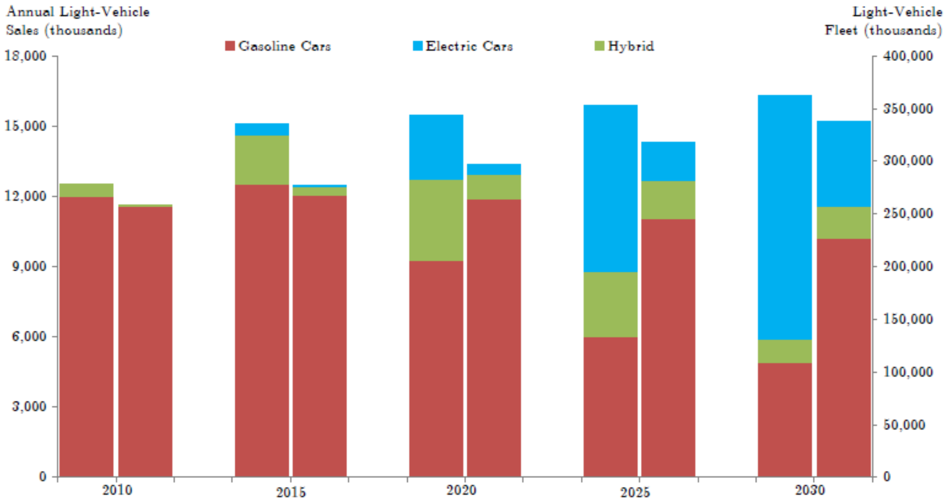


Figure 4. Annual vehicle sales forecast (light duty vehicles). UC Berkeley, 2009.

These EV sales projections from the report need to be transformed into charging demand that can be captured by these dedicated charging sites. To do this transformation, the following assumptions are made:

- It is expected that the first EV vehicles will hit the market by 2012.
- 20% of total EV owners will drive more than 100 miles in a daily commute (these customers will need the availability of the dedicated charging sites).[1]

---

[1] According to report Electric Vehicles in the United States, a new model with forecasts to 2030. Center for Entrepreneurship & Technology. University of California, Berkeley

- Electric Vehicles have a 10 year expected life.

The proposed transformation model is:

Can’t read equation, asked many times to correct.

millions.

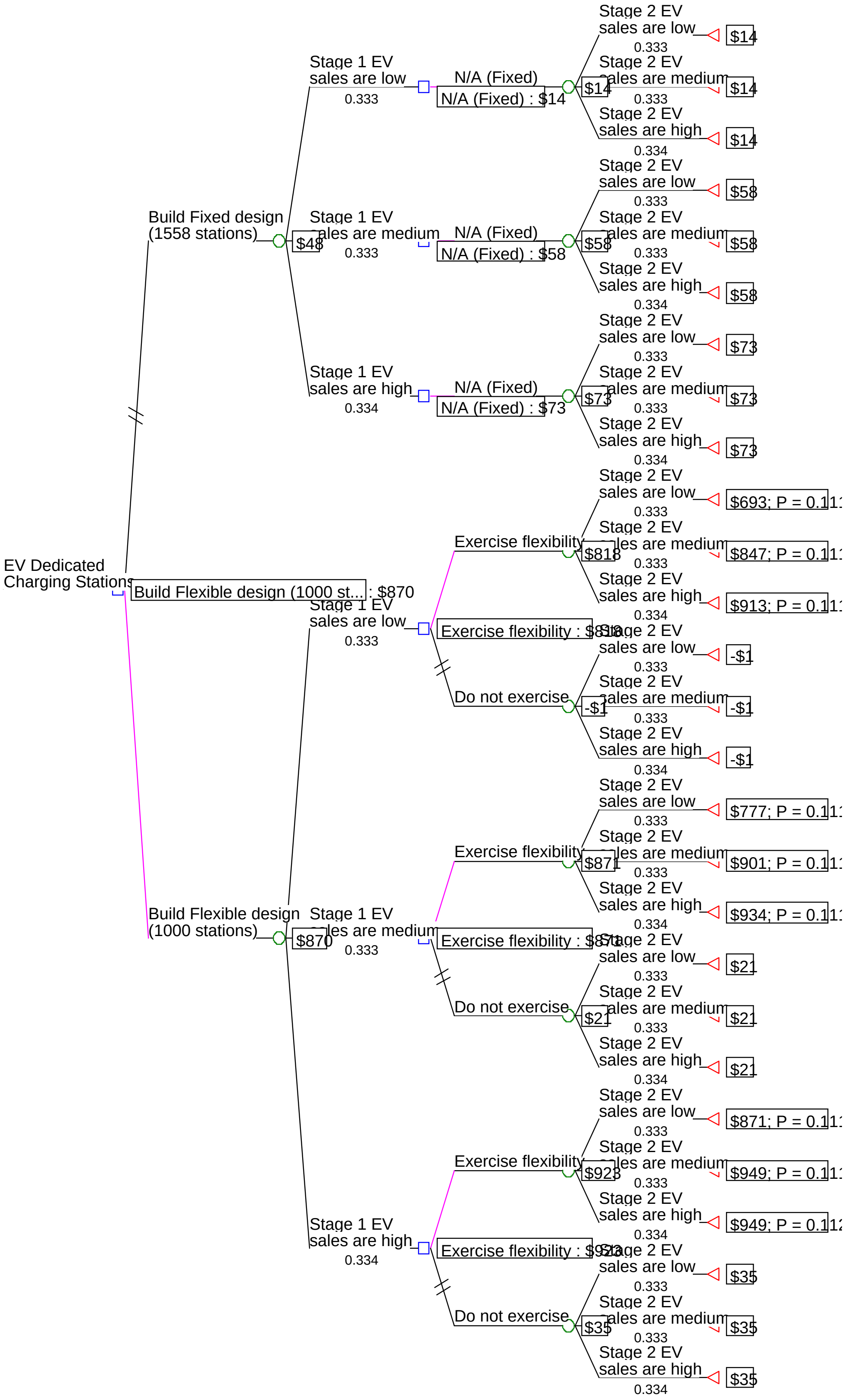


Figure 8. Decision Tree Fixed vs. Flexible design (NPV, $ millions).

Using the NPV values and the probabilities from the outputs of the decision tree, VARG curves can be plotted. Figure 9 shows these plots.

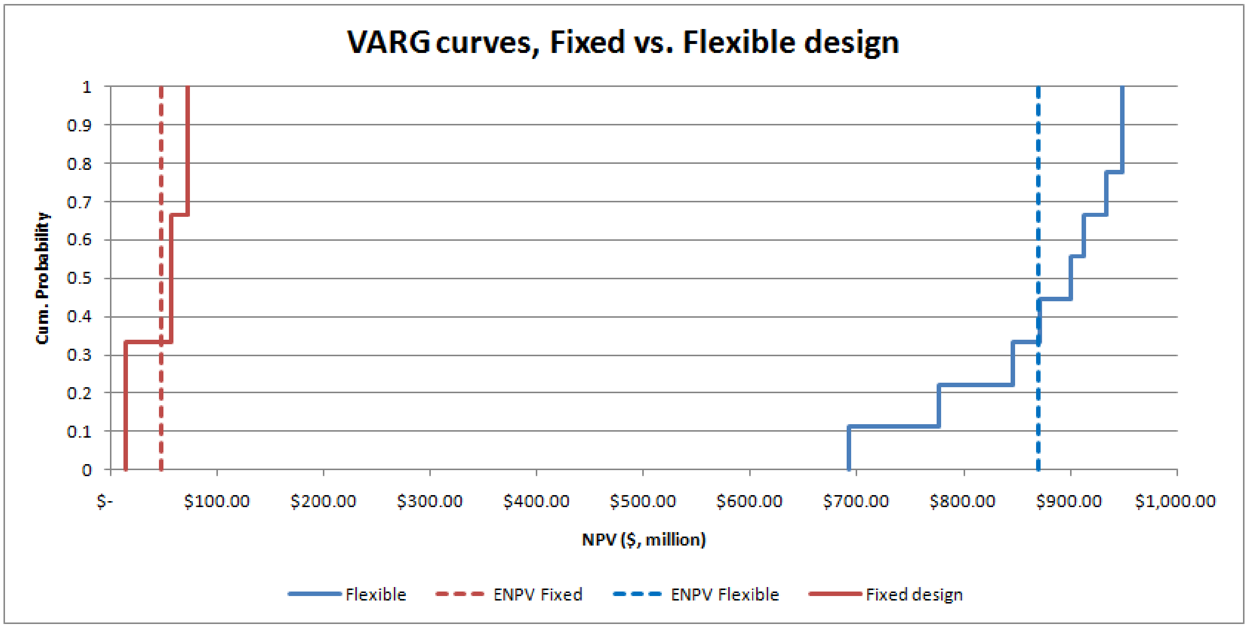


Figure 9. VARG graph, Fixed vs. Flexible design

Multidimensional Valuation

Table 6. Multidimensional valuation table, Fixed Design vs. Flexible Design.

	Fixed Design (1558 Level II charging stations)	Flexible Design (1000 upgradeable charging stations)	Comparison
CAPEX - Initial Investment [$, million]	($190.86)	($150.00)	Flexible design is better
Expected NPV [$, million]	$48.09	$870.36	Flexible design is better
Minimum NPV [$, million]	$13.78	$693.05	Flexible design is better
Maximum NPV [$, million]	$72.67	$949.06	Flexible design is better

Conclusions – Decision Tree Analysis

It is clear in both tools (VARG curve plots and Multidimensional valuation table) that the Flexible design is by all means better than the fixed design. The flexible design allows investing a smaller amount of money by building fewer stations at time zero. Also, by exercising flexibility at the end of stage 1 in the flexible design, the project would be able to capitalize the upside of the demand from 2016 and beyond by significantly increasing the charging capacity of each site. The minimum and the maximum NPV that can be expected are also better in the flexible design.

Lattice analysis

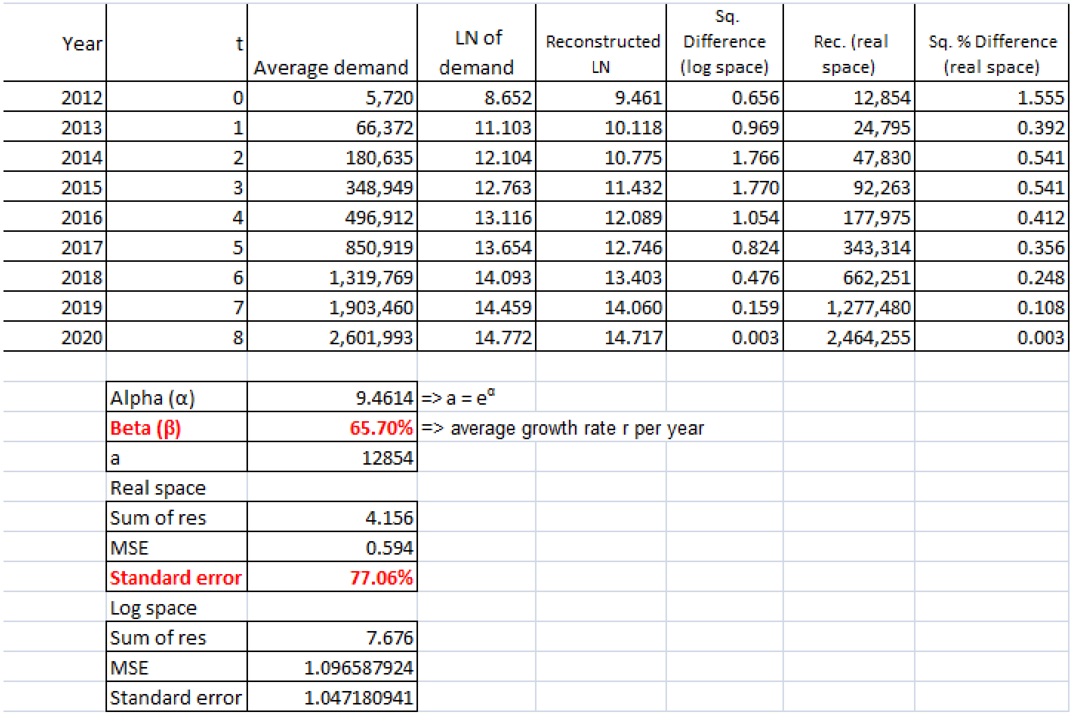
Model assumptions

- The major uncertainty to model in this application is the demand for charging Electric Vehicles.
- Total number of periods is 8.
- Discount rate is 12% compounded annually.
- **The flexible design has a call option of upgrading the charging stations to Level III.**
- Flexible and Fixed designs have same amount of charging facilities. The number of facilities does not change during the project. Given these conditions, the number of stations was optimized for the fixed design: 247 facilities (to get the best ENPV using the Lattice model).
- Once flexibility is exercised (flexible design), the change cannot be reverted.

Lattice analysis model

The demand model explained in the uncertainty description part, considers three scenarios each year: Low charging demand, Medium charging demand and High charging demand (see Figure 5). To find the Lattice parameters, values for v and σ were calculated from the demand model. Excel was used to do the proper regressions to find the values for these parameters. Calculations are shown in Table 7 and on Figures 10 and 11.

Table 7. Lattice parameters calculation



Year	t	Average demand	LN of demand	Reconstructed LN	Sq. Difference (log space)	Rec. (real space)	Sq. % Difference (real space)
2012	0	5,720	8.652	9.461	0.656	12,854	1.555
2013	1	66,372	11.103	10.118	0.969	24,795	0.392
2014	2	180,635	12.104	10.775	1.766	47,830	0.541
2015	3	348,949	12.763	11.432	1.770	92,263	0.541
2016	4	496,912	13.116	12.089	1.054	177,975	0.412
2017	5	850,919	13.654	12.746	0.824	343,314	0.356
2018	6	1,319,769	14.093	13.403	0.476	662,251	0.248
2019	7	1,903,460	14.459	14.060	0.159	1,277,480	0.108
2020	8	2,601,993	14.772	14.717	0.003	2,464,255	0.003

Alpha (α)	9.4614	=> $a = e^{\alpha}$
Beta (β)	**65.70%**	=> average growth rate r per year
a	12854	
Real space		
Sum of res	4.156	
MSE	0.594	
Standard error	**77.06%**	
Log space		
Sum of res	7.676	
MSE	1.096587924	
Standard error	1.047180941	

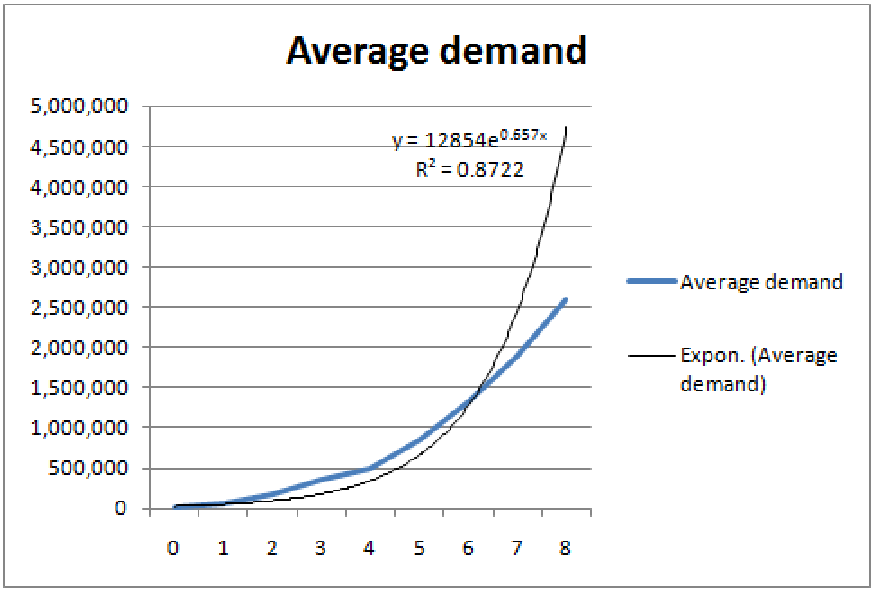


Figure 10. Average demand, regression analysis

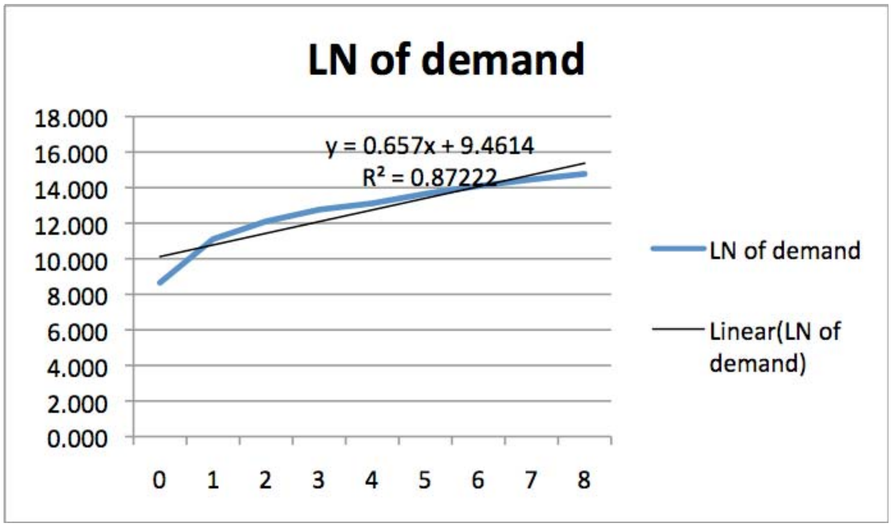


Figure 11. Log transformation of demand, regression analysis

Lattice parameters:

Values	
u	2.161
d	0.463
p	0.926

Using the data above, the Lattice model was calibrated to model the uncertainty under study (dedicated charging sites demand). Table 8 shows the Lattice models generated for demand and for probability.

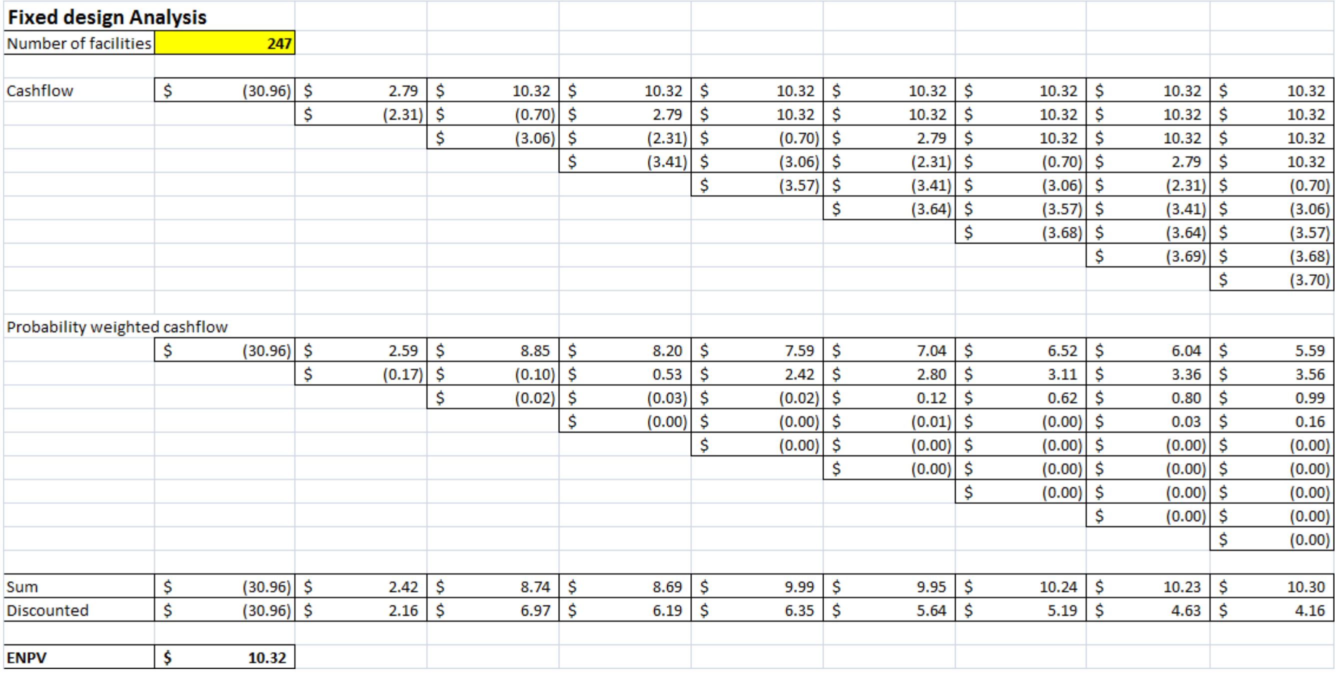
Table 8. Lattice models for charging demand and for probability.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5	t = 6	t = 7	t = 8
Period	0	1	2	3	4	5	6	7	8
Demand	5,720	12,361	26,712	57,725	124,744	269,571	582,545	1,258,882	2,720,449
		2,647	5,720	12,361	26,712	57,725	124,744	269,571	582,545
			1,225	2,647	5,720	12,361	26,712	57,725	124,744
				566.80	1,224.86	2,646.92	5,720.00	12,360.94	26,712.05
					262.3	566.8	1,224.9	2,646.9	5,720.0
						121.37	262.29	566.80	1,224.86
							56.16	121.37	262.29
								25.99	56.16
									12.03
Probability	1.000	0.926	0.858	0.795	0.736	0.682	0.632	0.585	0.542
		0.074	0.137	0.190	0.234	0.271	0.302	0.326	0.345
			0.005	0.015	0.028	0.043	0.060	0.078	0.096
				0.000	0.001	0.003	0.006	0.010	0.015
					0.000	0.000	0.000	0.001	0.002
						0.000	0.000	0.000	0.000
							0.000	0.000	0.000
								0.000	0.000
									0.000

Fixed Design Analysis – ENPV

Using the Lattice models shown in Table 8, and the assumptions described before (costs, revenues and 247 charging sites), the ENPV was calculated for the fixed design. Detailed results are found in Table 9.

Table 9. ENPV calculation – Fixed design.

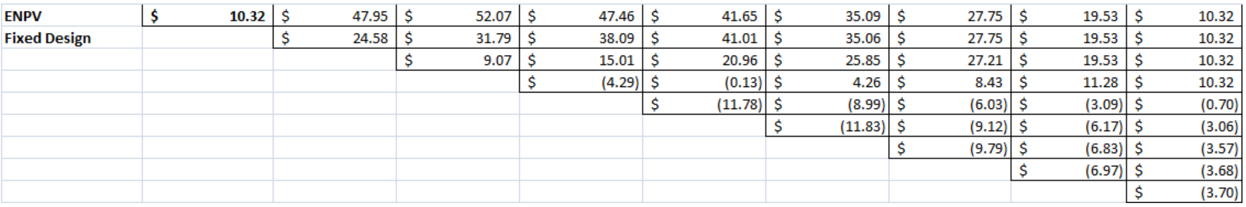


Fixed design Analysis									
Number of facilities	247								
Cashflow	$ (30.96)	$ 2.79	$ 10.32	$ 10.32	$ 10.32	$ 10.32	$ 10.32	$ 10.32	$ 10.32
		$ (2.31)	$ (0.70)	$ 2.79	$ 10.32	$ 10.32	$ 10.32	$ 10.32	$ 10.32
			$ (3.06)	$ (2.31)	$ (0.70)	$ 2.79	$ 10.32	$ 10.32	$ 10.32
				$ (3.41)	$ (3.06)	$ (2.31)	$ (0.70)	$ 2.79	$ 10.32
					$ (3.57)	$ (3.41)	$ (3.06)	$ (2.31)	$ (0.70)
						$ (3.64)	$ (3.57)	$ (3.41)	$ (3.06)
							$ (3.68)	$ (3.64)	$ (3.57)
								$ (3.69)	$ (3.68)
									$ (3.70)
Probability weighted cashflow									
	$ (30.96)	$ 2.59	$ 8.85	$ 8.20	$ 7.59	$ 7.04	$ 6.52	$ 6.04	$ 5.59
		$ (0.17)	$ (0.10)	$ 0.53	$ 2.42	$ 2.80	$ 3.11	$ 3.36	$ 3.56
			$ (0.02)	$ (0.03)	$ (0.02)	$ 0.12	$ 0.62	$ 0.80	$ 0.99
				$ (0.00)	$ (0.00)	$ (0.01)	$ (0.00)	$ 0.03	$ 0.16
					$ (0.00)	$ (0.00)	$ (0.00)	$ (0.00)	$ (0.00)
						$ (0.00)	$ (0.00)	$ (0.00)	$ (0.00)
							$ (0.00)	$ (0.00)	$ (0.00)
								$ (0.00)	$ (0.00)
									$ (0.00)
Sum	$ (30.96)	$ 2.42	$ 8.74	$ 8.69	$ 9.99	$ 9.95	$ 10.24	$ 10.23	$ 10.30
Discounted	$ (30.96)	$ 2.16	$ 6.97	$ 6.19	$ 6.35	$ 5.64	$ 5.19	$ 4.63	$ 4.16
ENPV	**$ 10.32**								

The expected net present value is **$10.32 million** for the fixed design.

Using dynamic programming in the Lattice model the present value at each state can be calculated (see Table 10, ENPV DA Lattice).

Table 10. ENPV DA Lattice tree for Fixed design.

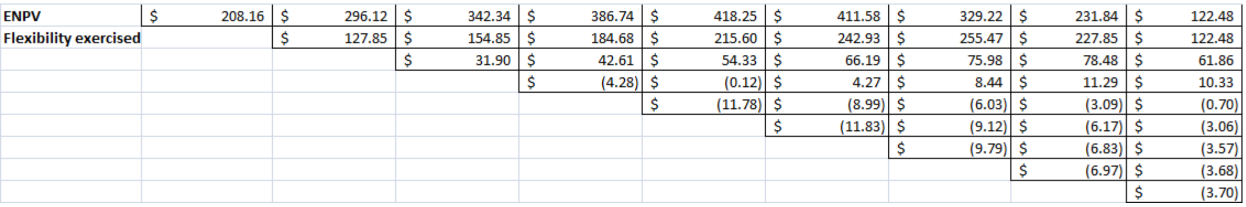


ENPV	**$ 10.32**	$ 47.95	$ 52.07	$ 47.46	$ 41.65	$ 35.09	$ 27.75	$ 19.53	$ 10.32
Fixed Design		$ 24.58	$ 31.79	$ 38.09	$ 41.01	$ 35.06	$ 27.75	$ 19.53	$ 10.32
			$ 9.07	$ 15.01	$ 20.96	$ 25.85	$ 27.21	$ 19.53	$ 10.32
				$ (4.29)	$ (0.13)	$ 4.26	$ 8.43	$ 11.28	$ 10.32
					$ (11.78)	$ (8.99)	$ (6.03)	$ (3.09)	$ (0.70)
						$ (11.83)	$ (9.12)	$ (6.17)	$ (3.06)
							$ (9.79)	$ (6.83)	$ (3.57)
								$ (6.97)	$ (3.68)
									$ (3.70)

Flexible Design Analysis

Dynamic programming approach was used to calculate the ENPV for the Flexible design, given we have the option to upgrade the charging stations to Level III. As input data for the Dynamic programming, a DA Lattice tree was created to calculate the PV at each state assuming a flexible design with flexibility option exercised since time zero (Table 11).

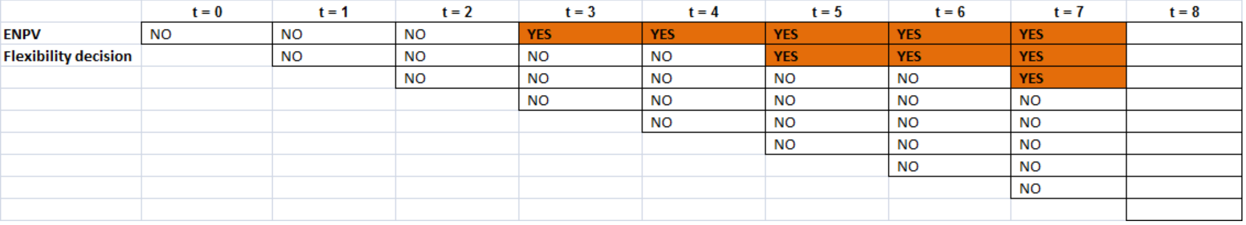
Table 11. ENPV DA Lattice tree for Flexible design with flexibility option exercised since time zero.



ENPV	$ 208.16	$ 296.12	$ 342.34	$ 386.74	$ 418.25	$ 411.58	$ 329.22	$ 231.84	$ 122.48
Flexibility exercised		$ 127.85	$ 154.85	$ 184.68	$ 215.60	$ 242.93	$ 255.47	$ 227.85	$ 122.48
			$ 31.90	$ 42.61	$ 54.33	$ 66.19	$ 75.98	$ 78.48	$ 61.86
				$ (4.28)	$ (0.12)	$ 4.27	$ 8.44	$ 11.29	$ 10.33
					$ (11.78)	$ (8.99)	$ (6.03)	$ (3.09)	$ (0.70)
						$ (11.83)	$ (9.12)	$ (6.17)	$ (3.06)
							$ (9.79)	$ (6.83)	$ (3.57)
								$ (6.97)	$ (3.68)
									$ (3.70)

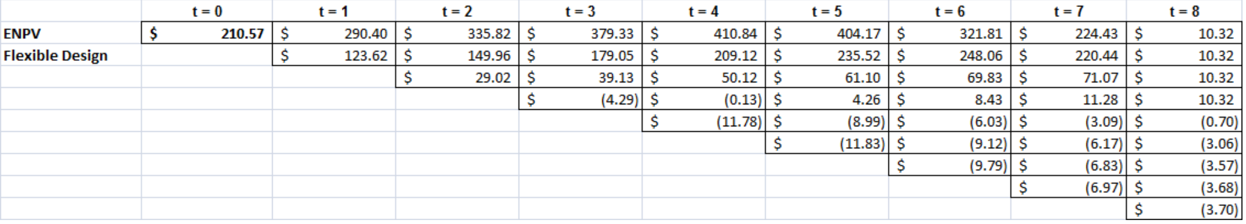
Using the information above, a DA Lattice tree for the flexible design with option was created (Table 13). The decision rule established was a comparison at each state between the present value of exercising flexibility (table 11) vs. the present value of not exercising it. If the former value is greater (considering exercising costs) than the latter, the flexibility option should be exercised. The flexibility indicator is shown in Table 12.

Table 12. DA Lattice tree – Flexibility Indicator (Dynamic Programming approach). When the indicator shows "YES", the option is exercised.



	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5	t = 6	t = 7	t = 8
ENPV	NO	NO	NO	YES	YES	YES	YES	YES	
Flexibility decision		NO	NO	NO	NO	YES	YES	YES	
			NO	NO	NO	NO	NO	YES	
				NO	NO	NO	NO	NO	
					NO	NO	NO	NO	
						NO	NO	NO	
							NO	NO	
								NO	

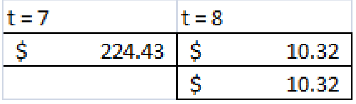
Table 13. DA Lattice tree – ENPV Flexible design (Dynamic Programming approach)



	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5	t = 6	t = 7	t = 8
ENPV	**$ 210.57**	$ 290.40	$ 335.82	$ 379.33	$ 410.84	$ 404.17	$ 321.81	$ 224.43	$ 10.32
Flexible Design		$ 123.62	$ 149.96	$ 179.05	$ 209.12	$ 235.52	$ 248.06	$ 220.44	$ 10.32
			$ 29.02	$ 39.13	$ 50.12	$ 61.10	$ 69.83	$ 71.07	$ 10.32
				$ (4.29)	$ (0.13)	$ 4.26	$ 8.43	$ 11.28	$ 10.32
					$ (11.78)	$ (8.99)	$ (6.03)	$ (3.09)	$ (0.70)
						$ (11.83)	$ (9.12)	$ (6.17)	$ (3.06)
							$ (9.79)	$ (6.83)	$ (3.57)
								$ (6.97)	$ (3.68)
									$ (3.70)

For the flexible design the ENPV is $210.57 million.

**As example, here is the calculation of the present value at the state in the first row of the column t=7 in the DA Lattice for the flexible design with option (table 13):



t = 7	t = 8
$ 224.43	$ 10.32
	$ 10.32

1. From this state, the Up state at t=8 is 10.32 and the down state at t=8 is 10.32. Probability up is 0.926, probability down is 0.074.
2. PV is calculated in the given state at t=7: (10.32*0.926 + 10.32*0.074)/(1+discount rate)+Cash flow at t=7. The result is 19.53.

3. Compare the result in 2 vs. the corresponding present value in table 11 minus the cost of exercising flexibility (231.84-7.41=224.43).
4. If the number calculated in 2 is smaller than 3, then the present value at this stage is the result of 3 and the flexibility option is exercised. If not, the present value is 2 and flexibility is not exercised. In this case 224.43 > 19.53, therefore the option should be exercised and the present value at this stage is 224.43 as shown above.

VARG curve / Cumulative Distribution of Outcomes

Using the data from the Lattice analysis above, a cumulative distribution (VARG curve) of the NPV of both designs was plotted:

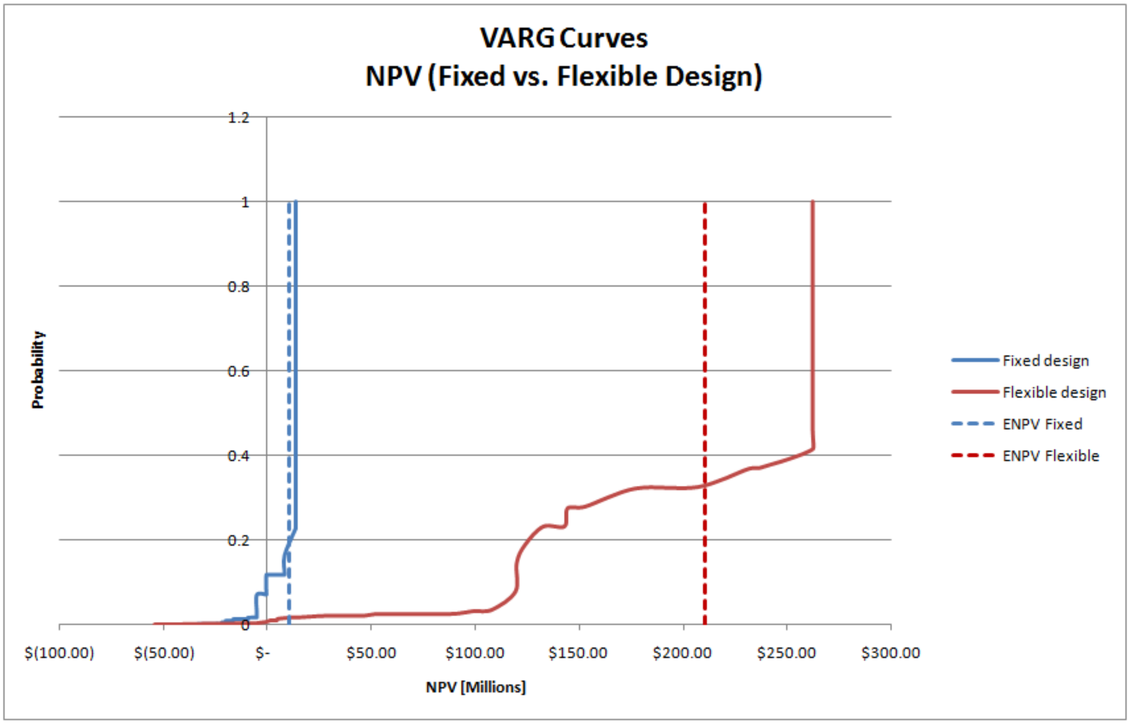


Figure 12. VARG curve, NPV (fixed vs. flexible design).

Multidimensional Valuation

Table 14. Multidimensional valuation table, Fixed Design vs. Flexible Design.

	Fixed Design (247 Level II charging stations)	Flexible Design (247 upgradeable charging stations)	Comparison
CAPEX - Initial Investment [$, million]	($30.96)	($37.75)	Fixed design is better
Expected NPV [$, million]	$10.32	$210.57	Flexible design is better

P_{10} NPV [$, million]	($0.56)	$119.8	Flexible design is better
P_{90} NPV [$, million]	$13.57	$262.39	Flexible design is better
Benefit-cost ratio	0.33	5.58	Flexible design is better

Value of call option

Value of call option = NPV with flexibility option - NPV without flexibility

Value of call option = $210.57 - $10.32 = $200.25 million

Conclusions Lattice Analysis

Looking at the VARG curves, it is clear that the flexible design is much better that the fixed design as most of the outcomes of the flexible design VARG curve are located at the right of the fixed design curve. Also, the ENPV (expected value) of the fixed design is much better. The flexible design is able to capitalize the upside of the rapidly rising demand.

This is confirmed in the multidimensional valuation table (Table 14), the flexible design is better in 4 out of 5 comparison categories. Specifically, the 10% VAR is better in the flexible design (minimize potential loss) and the 10% VAG (P_{90}) is better in the flexible design (better upside potential). Although the fixed design has lower CAPEX, the benefit-cost ratio of the flexible design is superior. The value of the call option is $200.25 million. One application of this value could be the as the upper limit for R&D spending of the enterprise to complete Level III charging development.

An insight I get from this is that we should always use multiple tools to compare projects (VARG + Multidimensional valuation table is a good option). The objective of using multiple tools is to compare the projects from different angles and avoid missing something important by using just one perspective.

Overall conclusions

Two analyses were carried out to evaluate the benefit of using flexibility in the design of dedicated charging sites for Electric Vehicles when facing uncertainty in the charging demand. In both cases, the flexible design demonstrated to yield better outcomes for the enterprise than the fixed design. First, we used 2-stage Decision Analysis (DA) comparing the NPV of a fixed design vs. a flexible design with the option to expand charging capacity at the end of stage 1. The flexibility option was to upgrade the technology in the charging stations to increase the charging capacity per site. One of the insights was that DA is a very flexible tool that can accommodate uncertainties and decisions of multiple types, but cat get too complicated if we use more than 3 stages (a DA with a stage per year would have been unmanageable).

Next, we used a Lattice analysis to compare a fixed design with a flexible one with a call option to expand by changing charging technology. It turned out that the flexible design had better outcome. The Lattice analysis with Dynamic programming was useful to determine in which point in time we should exercise the call option by evaluating the system in multiple states. This tool has the limitation that can handle only one uncertainty and relies on path independence. If in the future we have to add other uncertainties in the model, Lattice won't be helpful. In this case we should look at doing a restructured decision tree analysis.

Also, a very important insight I get from this project is that we should use multiple tools to compare projects. We should recognize that not all tools are applicable in the same situation. By using multiple analysis tools we gain the ability to see the picture from different perspectives in order to take a better decision.

I enjoyed doing this project as I applied some of the tools we learned in ESD.71 into real data. In the other hand, this project helped me to understand how to value flexibility and to use multiple criteria to compare projects. Certainly, the acquired knowledge and tools will be assets back at work.

References:

- http://gas2.org/2009/07/07/the-ev-infrastructure-chicken-and-egg-problem-resolution/
- http://auto.howstuffworks.com/electric-car5.htm
- http://www.betterplace.com/
- http://www.coulombtech.com
- http://green.autoblog.com/2006/12/11/renault-nissan-to-build-an-electric-car-in-2010/
- http://www.detnews.com/apps/pbcs.dll/article?AID=/20090202/AUTO01/902020354/1148/rss25
- http://www.huffingtonpost.com/2009/03/20/obamas-electric-vehicles_n_177286.html
- http://www.thefreelibrary.com/Charging+ahead:+electric-vehicle+charging+stations+popping+up+all...-a019707503
- http://www.mge.com/Images/PDF/Electric/other/ElectricVehicleChargingStations.pdf