This project aims to evaluate the introduction of flexibility into designing grid-scale solar power plants. There exist certain forms of tracking PV panels that can be manually tracked/moved in order to increase the output of the plant. At the same time though, certain costs are incurred to introduce flexibility by employing manual labor and hence through this project, taking into account certain core uncertainties in this system, we hope to address whether employing manual labor will help the overall financials of the PV project.
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1. Introduction & System Definition

While working in India this summer at an Independent Power Producer (IPP), I was exposed to grid-scale project development, particular in the solar space. The Ministry of New & Renewable Energy (MNRE) in India created a National Solar Mission in 2008 with the aim of generating 20,000 MW of grid connected solar power by 2022 (Government of India, 2009). Consequently, the MNRE established 3 phases of growth with corresponding targets. Within the current phase, which lasts till 2013, project developers primarily compete for grid-scale solar projects of 5MW capacity each.

While evaluating and developing project proposals to submitting to the MNRE, I was developing an existing solar project evaluation model and utilizing the same to evaluate project financials and the viability of bidding in for these projects under the Ministry’s rules. While doing so, it was easy to understand that a number of the factors that were considered in the model were uncertain and more importantly, financial decisions were often made ignoring the uncertainty that was integral to these projects and their characteristics. Having the opportunity to take ESD.71 in the semester following this summer experience, I thought it would be extremely useful to understand and characterize the uncertainty in these models and come up with a flexible design approach to deal with the same.

Hence, the system is question is a 5MW grid connected PV plant. The system is represented by an excel-based financial model that deals with certain inputs (technical and financial) and provides the user with certain economic indicators as outputs.

<table>
<thead>
<tr>
<th>Model Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical and Financial</td>
</tr>
<tr>
<td>Plant capacity, efficiency, Costs of equipment, labor cost, interest rate, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial</td>
</tr>
<tr>
<td>Net Present Value (NPV), Equity Internal Rate of Return (IRR), etc.</td>
</tr>
</tbody>
</table>

Figure 1 - System Inputs and Outputs

In order to simplify the system to an extent to make this project feasible given time constraints, certain limitations to the system imply. Although the model is fairly sophisticated and can
incorporate several equity holders into one project, account for refinancing, etc. we will use it a black box primarily that takes in certain fairly obvious inputs to provide certain economic indicators as outputs.

Finally, keep in mind that the system is valid for a period of 25 years, and the Internal Rate of Return (IRR) will be used as the economic evaluation metric. IRR is a standard metric used by project developers to evaluate the feasibility of their projects. Given the high debt associated with such infrastructure projects, IRR provides them a metric to easily compare with the cost of capital i.e. interest rates.
2. Sources of Uncertainty

As mentioned, the system in question is a 5MW grid connected PV plant. In order to simplify the system to an extent to make this project feasible given time constraints, certain limitations to the system imply as previously mentioned.

2.1 Factors of uncertainty

To simplify the system, 3 variables for uncertainty will be considered. The three variables that are being considered are the following:

- **PLF (Plant Load Factor)** – the PLF is a number that represents the output of the system as a percentage of the peak output capacity. The PLF is usually used as a fixed input into the model. However, the PLF depends on a variety of technical (system efficiency, choice of panels, inverters, etc.) and meteorological conditions (weather, wind, etc.) and is certainly not fixed over the lifetime of a project.

- **EPC costs (Engineering, Procurement and Construction costs)** – the EPC costs represent the costs of the PV panels and the Balance of Plant (BOP). Given recent drop in PV panel prices, these costs are uncertain and depend upon the choice of equipment manufacturer, market conditions, etc.

- **Interest rates** – Interest rates are close to 12.5% in India and are a big reason why large-scale infrastructure projects are getting difficult to carry out. However, over the last few months there has been a variation of close to 100 basis points and developers are even looking for ways to raise foreign capital at lower interests. Given the important of interest to these projects, this will be the third factor of uncertainty that we consider.

2.2 Uncertainties and Sensitivity Analysis

As mentioned earlier, three variables were considered when evaluating system uncertainties. As a first step, based on an existing base model with no uncertainties, a sensitivity analysis was carried out on all three variables. The sensitivity analysis took the form whereby each variable was varied from +10% to -10% of its original value with a step of 1%, keeping all other factors constant. The IRR was evaluated as the output and the result of the sensitivity analysis.
As it can be seen in the graph above, the PLF (red bar) has the highest impact on the system output and hence is the most sensitive of the three underlying parameters. As a result, for the sake of this project, uncertainty will be introduced into the PLF. The impact of this uncertainty on the system will be analyzed and then a flexible design will be introduced to evaluate its value and compare it to the fixed design.

### 2.3 Characterizing uncertainty

In order to understand how the uncertainty of the PLF will be characterized, it is important to gain an understanding of the process of how the PLF is usually calculated. During the project development process, developers usually contract work to consultants who prepare Detailed Project Reports (DPR’s) whereby they evaluate the PLF based on the land where the developer will build a proposed project, the technology in use, meteorological data, etc.

The best way to understand if these predictions are close to observations would be to simply compare the DPR projection’s with obtained data once projects are commissioned. However, given the lack of operational grid-scale PV projects in data, there simply does not exist enough data to make a valid estimation of the uncertainty involved with such predictions.

Fortunately, the Indian Ministry had developed certain pilot projects before announcing the National Solar Mission and had collected some data on the same. They released a report that highlighted some of this information (Ministry of New & Renewable Energy (MNRE), India, 2011). Some of this information is represented in the table below:
Table 1 - MNRE observational data on demonstration PV plants

<table>
<thead>
<tr>
<th>Project Developer</th>
<th>Actual PLF% (yearly average)</th>
<th>Highest PLF% (for a 1 month period)</th>
<th>Lowest PLF% (for a 1 month period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBGEDCL</td>
<td>12.29%</td>
<td>14.54%</td>
<td>10.52%</td>
</tr>
<tr>
<td>Azure</td>
<td>17%</td>
<td>20.7%</td>
<td>-</td>
</tr>
<tr>
<td>Mahagenco</td>
<td>15.39%</td>
<td>17.8%</td>
<td>-</td>
</tr>
<tr>
<td>Reliance</td>
<td>19%</td>
<td>22%</td>
<td>-</td>
</tr>
</tbody>
</table>

Although the above data represents statistics based on only 1 yr of actual observations, it provides us a starting point to evaluate the uncertainty associated with PLF numbers. The actual PLF numbers line up pretty well with the expected PLF based on the same report. However, there seem to be variations in the upper and lower limit. Developers usually base their model on one particular fixed number and hence do not account for any form of uncertainty or range.

Taking into account the above data, and its limitations, we decided to base our range as follows: we will assume the mean of the data to be the mean as based by on the DPR. However, that mean will be fed into a normal distribution with a standard deviation of 1%. If we were to use such an analysis for the WBGEDCL project, our PLF would take this form:

![Figure 3 - WBGEDCL Project with uncertainty](image)

Although the maximum and minimum through our simulation exceed the range of the data in the table above for the WBGEDCL case, given that the above data was obtained by averaging 30 days worth of observations, our distribution seems to be an approximate enough estimate to allow us to understand the role of uncertainty in such projects. Unfortunately, given the lack of...
observational data to develop a more formalized understanding of PLF uncertainty, we chose to model the distributions with expected means as reported and with a standard deviation of 1%.
3. Fixed and Flexible Designs

3.1 Model Specifications

Although the section above highlights some of the factors of uncertainty that will be evaluated, it does not address the flexibility that will be introduced to the system. To begin with, it is important to remember that none of the above mentioned underlying parameters currently exist as uncertainty distributions and hence the first step to model this system (creating the base model without flexibility) will be to incorporate the relevant uncertainty distributions into the pre-existing model that was used earlier in the summer.

The pre-existing model represents a 5MW project that the developer is carrying out with input costs and an output IRR that meets the developer’s requirements and thresholds. Those inputs will be used to create our base case.

The PLF is assumed to be 19.6% with a depreciation of 0.8% p.a. for the life-time of 25 years. Some of the other important inputs and the project IRR (our economic output of choice) are highlighted below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPC Cost</td>
<td>Input</td>
<td>Rs. 103 Million/MW</td>
</tr>
<tr>
<td>PLF</td>
<td>Input</td>
<td>19.6%</td>
</tr>
<tr>
<td>Interest rate</td>
<td>Input</td>
<td>10% 1 yr after Commission</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Equity IRR</td>
<td>Output</td>
<td>13%</td>
</tr>
</tbody>
</table>

As mentioned earlier, the PLF will be modified to account for uncertainty and then flexibility will be introduced into the system in order to make a comparison b/w the fixed and flexible design.

### 3.2 Flexibility in Design Choice

As highlighted previously, there exists a need to model the PLF’s as a distribution rather than as a fixed number. Given that some of reason behind the same and the method adopted in this project to model the distribution have been sited already, we now wish to focus on the flexible design choice that the project will be evaluating.

There exist certain PV panels that are manually tracked\(^1\) i.e. they can be moved by manual labor in order to increase the output they can capture. Hence, project developers have the ability to make a decision on whether they will employ manual labor with an expectation of extracting a greater amount of energy from such panels. It is not atypical for panels to be manually moved as seasons change in order to allow the panels to face as large as possible amount of incident rays from the sun.

Hence, at a macro level, our project will evaluate the following: should manual labor be employed to extract possibly more output while incurring higher costs of employing labor to move these panels while keeping in mind the uncertainties of the system.

The system will work with certain assumptions related to how often panels will be moved, costs associated with the same, etc. These assumptions have been described in a latter section in more detail.

\(^1\) (Photovoltaic Systems, 2011)
4. Simulation Setup

For the purpose of evaluating flexibility in grid-scale PV plants in India, we will begin with a model that was previously used for developing a 5MW grid connected plant in Rajasthan. The plant was recently commissioned and the numbers being used in our analysis are those of the same plant (I was working on this particular case at my internship this summer).

Hence, our reference point for our data stems from that particular project. Some of the main data variables have been highlighted in Table 2.

4.1 The Base Case

The system has broken down into 5 time periods (each of 5 yrs) and hence a total project lifetime of 25 years. Hence, the variable of uncertainty (PLF) has been broken down into 5 different variables, each representing a particular time period.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Base PLF without Uncertainty</th>
<th>Base with PLF Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yrs 1-5</td>
<td>19.6%</td>
<td>S.D. with mean = 19.6%, Variance = 1%</td>
</tr>
<tr>
<td>Yrs 6-10</td>
<td>18.8%</td>
<td>S.D. with mean = 18.8%, Variance = 1%</td>
</tr>
<tr>
<td>Yrs 11-15</td>
<td>18.1%</td>
<td>S.D. with mean = 18.1%, Variance = 1%</td>
</tr>
<tr>
<td>Yrs 16-20</td>
<td>17.4%</td>
<td>S.D. with mean = 17.4%, Variance = 1%</td>
</tr>
<tr>
<td>Yrs 21-25</td>
<td>16.6%</td>
<td>S.D. with mean = 16.6%, Variance = 1%</td>
</tr>
</tbody>
</table>

Base case when comparing to flexible design

It is assumed that the Base PLF without uncertainty decreases at the rate of 0.8% p.a. as technology gets older. The simulation was set up and run for a total of 500 iterations.
Figure 5 - Base Case PLF input for years 1-5

Figure 6 - Base Case PLF input for years 6-10
Figure 7 - Base Case PLF input for years 11-15

Figure 8 - Base Case PLF input for years 16-20
As mentioned earlier, the equity IRR was used as the economic indicator of choice for such large scale infrastructure projects. The output variable of choice (the IRR) is shown below:

This Equity IRR now forms the base IRR that will be compared with the IRR obtained when the option of flexibility is available. The mean is about 13% with a standard deviation of 0.8%.
4.2 The Flexible Case

As described earlier, the flexibility in question is whether to employ a labor force to manually move panels to potentially extract more output than if the panels were not moved or tracked. Assuming that labor is employed every quarter i.e. 4 times a year, we can come up with the following cost of labor or flexibility:

Table 4 - Cost of labor for flexibility

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Total Size of plant:</td>
<td>5MW</td>
<td></td>
</tr>
<tr>
<td>(b) Size of each panel:</td>
<td>200W</td>
<td></td>
</tr>
<tr>
<td>(c) No. of panels:</td>
<td>~25000 (a)/(b)</td>
<td></td>
</tr>
<tr>
<td>(d) Total hrs/shift:</td>
<td>~6250 hrs (assuming 15 mins per panel shift) (c)/6</td>
<td></td>
</tr>
<tr>
<td>(e) No. of days/shift:</td>
<td>10 days (assume each tracking operation lasts for two weeks)</td>
<td></td>
</tr>
<tr>
<td>(f) No. of hrs/day</td>
<td>~625 (d)/(e)</td>
<td></td>
</tr>
<tr>
<td>(g) No. of labor</td>
<td>~78 (assuming 8 hr working days) (f)/8</td>
<td></td>
</tr>
<tr>
<td>(h) No. of shifts a yr:</td>
<td>4 (once a quarter)</td>
<td></td>
</tr>
<tr>
<td>(i) Cost of Labor/Hr:</td>
<td>Rs 30/hr</td>
<td></td>
</tr>
<tr>
<td>(j) Total Cost:</td>
<td>~Rs 750,000 (e)(f)(h)(i)</td>
<td></td>
</tr>
<tr>
<td>(k) Cost/MW:</td>
<td>~Rs 150,000 (j)/(a)</td>
<td></td>
</tr>
</tbody>
</table>

Hence, we have calculated in approximation that the cost of flexibility of Rs 0.75 Million/yr or rather Rs 3.75 Million for a period of 5 yrs. Although this is a rough estimate, it does give us a starting point. If we were to employ labor every year over a 25 year to track panels, it would total a cost of Rs 19 Million which is about 3.5% of the total project cost.

Similarly, a methodology needs to be developed to capture the potential additional benefit of using labor to track the PV panels. Intuitively speaking, shifting panels to track the sun better should increase the potential output captured. For the sake of simplicity, this has been modeled as a gamma distribution with the same mean but further potential PLF on the right hand side of the distribution. The gamma distribution PLF for yrs 1-5 is shown below. This can be compared to the earlier distribution for years 1-5 to gain an understanding of the difference between the cases.
Figure 11 - PLF for flexible design over years 1-5

Figure 12 - PLF for flexible design over years 6-10
Figure 13 - PLF for flexible design over years 11-15

Figure 14 - PLF for flexible design over years 16-20
The difference between the normal distributions (base case) and gamma distributions (flexible case) is summarized below:

Table 5 - Comparing PLF for fixed and flexible designs

<table>
<thead>
<tr>
<th>Years</th>
<th>Fixed Design</th>
<th>Flexible Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Min.</td>
</tr>
<tr>
<td>1-5</td>
<td>19.60</td>
<td>15.70</td>
</tr>
<tr>
<td>6-10</td>
<td>18.82</td>
<td>15.69</td>
</tr>
<tr>
<td>11-15</td>
<td>18.10</td>
<td>15.07</td>
</tr>
<tr>
<td>16-20</td>
<td>17.40</td>
<td>14.63</td>
</tr>
<tr>
<td>21-25</td>
<td>16.6</td>
<td>14.05</td>
</tr>
</tbody>
</table>

The two boxes in red represent the 5%-95% range of the values for the fixed and flexible cases. As it can be seen, the 5% values are relatively close whereas the 95% numbers vary to a larger extent. This indicates that the potential for extracting more output by tracking the panels could possibly exceed the costs associated with it and hence make the flexible choice feasible.

Hence the flexibility question becomes the following: What is the trade-off between employing labor at the cost of Rs 0.75 Million/yr (for periods of 5 years at a time) to increase the output of a plant given inherent uncertainty associated with the PLF of a plant.
5. Simulation Analysis

Once the project developer can account for the costs of flexibility i.e. labor costs as shown above, the developer has the following choices and decisions to make: For what period of 5 yrs should the developer decide to employ manual labor? When should the developer decide to exercise the option of flexibility?

5.1 Intuition behind cases

There were a few ways of looking at this problem. To begin with, we carried out some analysis for a variety of cases (flexibility employed only for 1st five years, all 25 years, 1st ten years, etc.) to get some sense of the value being added. The “if” statement being used to justify going with flexibility can be described in the following manner: if the expected IRR with using labor exceeded the expected IRR with no labor i.e. the base case, flexibility would be exercised.

Very soon, it became clear that the option of flexibility did not lead to an increase in the expected IRR. There were no cases where the expected IRR was higher and hence our flexibility decision always returned a NO choice. In order to understand this better, it was important to understand if the base case was stochastically dominant to all other cases. Fortunately, that was not the case. Hence, it became important to justify the cases that the project will study and hence cases where the fixed and flexible designs will be evaluated. Given the 5 time periods the project was divided into, there were a total of 31 choices. With the ‘if’ statement returning the decision to not employ flexibility for all 31 cases, we decided to justify some cases that we would like to evaluate more specifically and understand the target curves of the same when compared to the base case.

To begin with, let us begin with some intuition behind this problem. Based on the way the model is set up, the developer makes a decision every five years on whether to employ labor for the next five years and then pays for the entire cost of 5 years at the beginning of the period. The developer may also see some potential benefit over that period depending on the uncertainties in the model. As project benefits get discounted over the years and keeping in mind the 25 year nature of this project, one may assume that employing labor in the first few years of the project may lead to higher potential IRR’s. Also, keeping in mind that technology degrades over the years, the potential to get a higher PLF is higher in the earlier years (as seen in the graphs above as well). Hence, our intuition would indicate that developers may seem higher potential returns if labor was employed in the first few years of the project.

In order to test this intuition, we decided to run the model with the flexible option for each of the 5 year periods separately.
Figure 16 - IRR with Flexibility over years 1-5

Figure 17 - IRR with Flexibility over years 6-10
Figure 18 - IRR with Flexibility over years 11-15

Figure 19 - IRR with Flexibility over years 16-20
Figure 20 - IRR with Flexibility over years 21-25

A summary of the results obtained is provided below:

**Table 6 - Summary of single period flexibility designs**

<table>
<thead>
<tr>
<th>Years</th>
<th>Minimum IRR</th>
<th>Maximum IRR</th>
<th>Mean IRR</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>9.58%</td>
<td>22.8%</td>
<td>12.6%</td>
<td>1.89%</td>
</tr>
<tr>
<td>6-10</td>
<td>9.59%</td>
<td>16.73%</td>
<td>12.47%</td>
<td>1.10%</td>
</tr>
<tr>
<td>11-15</td>
<td>10.16%</td>
<td>15.24%</td>
<td>12.46%</td>
<td>0.904%</td>
</tr>
<tr>
<td>16-20</td>
<td>10.41%</td>
<td>14.54%</td>
<td>12.47%</td>
<td>0.772%</td>
</tr>
<tr>
<td>21-25</td>
<td>10.19%</td>
<td>14.80%</td>
<td>12.47%</td>
<td>0.761%</td>
</tr>
</tbody>
</table>

As it can be seen from the above table, flexibility or the choice to employ labor increases the maximum possible IRR if the option is exercised early on in the life of the project. As our intuition suggested the de-rating of technology and impact of discounting decreases the value of flexibility as the time proceeds.

### 5.2 Test Cases

Given the nature of this problem and 5 time periods for decision making, there are a total of 31 choices of flexibility for the developer! We discussed 5 of these choices in the previous section and came to the conclusion that flexibility is likely to be valued is exercised early on in the project life. In this section, we wish to decide on the flexibility cases that will be analyzed.

**Case 1: Labor for first 5 years only**
In this case, the developer can decide to employ labor for the 1st five year period. Given the nature of technology degradation and financial discounting, it is expected that the developer may see potential benefit if flexibility is exercised in this case.

**Case 2: Labor for first 10 years only**

This case expands on the first case but allows the developer to be flexible for the first ten years rather than just the first five years. This will allow us to get an understanding of how stretching the time horizon for flexibility impacts the project financials.

**Case 3: Labor for all 25 years**

This assumes that the developer employs labor to manually move the panels for all 25 years and hence this case would form the extreme flexibility case i.e. where flexibility is exercised over the entire lifetime of the project.

Ideally, we would have automated this process and hence flexibility would be exercised by the model whenever the economic indicators made the case for flexibility i.e. flexible IRR > base case IRR. However, it was clear than the expected value of the flexible IRR (regardless of case) is always lower than the expected value in the base case. Hence, these three cases have been picked in order to gain an understanding of the target curves and possible situations where flexibility may make sense based on the risk profile of the developer taking such decisions.
6. Evaluation Metrics

6.1 Evaluation, Target Curve

To begin with, we wish to plot the equity IRR for all the four cases:

- Case A: Base Case
- Case B: Flexibility exercised in years 1-5
- Case C: Flexibility exercised in years 1-10
- Case D: Flexibility exercised in years 1-25

![Figure 21 – Case A: Base Case IRR]
Figure 22 – Case B: Flexibility exercised in years 1-5

Figure 23 – Case C: Flexibility exercised in years 6-10
The results are summarized below:

Table 7- Evaluating Flexibility Summary

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Mean IRR</th>
<th>Min. IRR</th>
<th>Std. Dev.</th>
<th>P5</th>
<th>P95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>13.02%</td>
<td>10.90%</td>
<td>0.825%</td>
<td>11.05%</td>
<td>14.45%</td>
</tr>
<tr>
<td>Flex in years 1-5</td>
<td>12.5%</td>
<td>8.45%</td>
<td>2.16%</td>
<td>10.03%</td>
<td>16.15%</td>
</tr>
<tr>
<td>Flex in years 1-10</td>
<td>12.5%</td>
<td>9.05%</td>
<td>2.04%</td>
<td>9.89%</td>
<td>16.07%</td>
</tr>
<tr>
<td>Flex in years 1-25</td>
<td>12.5%</td>
<td>8.70%</td>
<td>2.12%</td>
<td>9.89%</td>
<td>16.34%</td>
</tr>
</tbody>
</table>

As it can be seen in the table above, the expected value is the greatest for the base case. The std. deviation is highest for the case where flexibility is exercised in the first five years – this is in line with our intuition as this is when the technology is most capable of providing largest PLF’s and is also when the benefits are least discounted. The 5% and 95% values also indicate that the base case is the most stable whereas the variation is greater for the other cases (more on these other criteria is explained in 6.2). Shown below are target curves to better illustrate the possible gains of flexibility. Keep in mind the following labeling convention:

- Case A: Base Case
- Case B: Flexibility exercised in years 1-5
- Case C: Flexibility exercised in years 1-10
- Case D: Flexibility exercised in years 1-25
Figure 25 - Target Curves (Base/Case A v/s Case B)

Figure 26 - Target Curves (Base/Case A v/s Case C)
As it can be seen through the above curves, the flexible cases examined are capable of providing a higher IRR about 25% of the time. All three flexible cases are relatively similar when compared to the base case.
The figure above is a zoomed in version of the target curves of the three flexible cases (B, C and D). As it can be seen the curves are relatively similar and the slight variations are hard to visualize at this resolution.

The above graph represents the base case in red compared to the three cases of flexibility. The red curve is dominant for about 75% of the curve and hence it would require a risk taking developer or someone with extreme certainty on the possibility of capturing further output through flexibility that would exercise such a choice.

6.2 Evaluation, Multiple Criteria

As shown above, the flexible choice provides the developer with higher IRR about 25% of the time. However, the target curves are simply one method of looking at the difference between the fixed and flexible design cases through the eyes of the economic indicator of choice – the IRR. Some other metrics to analyze include the mean, min, max, std. dev. P5 and P95. The table below summarized the results based on these sets of criteria.
Table 8 - Results summary

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>Std. Dev.</th>
<th>P5</th>
<th>P95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case (Case A)</td>
<td>13.02%</td>
<td>10.90%</td>
<td>15.42%</td>
<td>0.825%</td>
<td>11.05%</td>
<td>14.45%</td>
</tr>
<tr>
<td>Flex in years 1-5 (Case B)</td>
<td>12.5%</td>
<td>8.45%</td>
<td>23.1%</td>
<td>2.16%</td>
<td>10.03%</td>
<td>16.15%</td>
</tr>
<tr>
<td>Flex in years 1-10 (Case C)</td>
<td>12.5%</td>
<td>9.05%</td>
<td>25.4%</td>
<td>2.04%</td>
<td>9.89%</td>
<td>16.07%</td>
</tr>
<tr>
<td>Flex in years 1-25 (Case D)</td>
<td>12.5%</td>
<td>8.70%</td>
<td>27.5%</td>
<td>2.12%</td>
<td>9.89%</td>
<td>16.34%</td>
</tr>
</tbody>
</table>

Mean: As it can be seen, the fixed design always provides a greater expected value. Although the means are only 0.5% apart, 13% is a relatively low hurdle rate in the large scale infrastructure industry and hence 12.5% could be felt as a lot lower than only a 0.5% change when compared to the fixed design.

Minimum and Maximum: Case B has the lowest minimum possible IRR. This isn’t surprising since this is the case where benefits or losses are discounted the least and since the technology is expected to degrade over time, the 1st five years provides a period critical to the return seen by the developer. Facing low PLF’s with high labor cost could lead to a case where the losses are further exaggerated. Cases C and D also have similar minimums and hence a developer who is risk averse may chose to stay away from these choices. Based on the target curves, there is a 60% probability for the flexible cases to return an IRR less than the mean of the base case (13%) and hence developers are likely to see returns lower than 13% if they exercise the flexibility option.

Std. Deviation, P5 and P95: As expected, the standard deviation is higher for the flexible projects. Case B sees the largest std. deviation. The explanation could be similar to that used above in understanding why Case B has the lowest minimum. However, all three flexible cases are relatively close in std. deviation and given that the simulation was only run for 500 numbers, this may not be statistically significant. The P5 and P95 numbers demonstrate the variation b/w the fixed and flexible designs. The numbers are relative close for all the flexible cases but the maximums shown in the table indicate that Case D has higher IRR to the right of P95 when compared to other cases. A risk taking developer looking to capture some of the low probability upside would find this information exciting!
7. Discussion of Results

As seen above, the results can be classified based on a variety of criteria. If we were to use the expected value as the indicator of choice, the fixed design turns out to be the most beneficial. However, the flexible cases do provide additional value but are accompanied by a low probability of the same.

Based on our assumptions and criteria, most developers may prefer to go with the fixed design. This result is a representation of the case modeled in this project and with different cases, and different set of assumptions, the results could obviously vary. Although most of the results and conclusion have been discussed in the previous section, this section highlights a few key takeaways from the results we obtained:

- **Choice depends on risk profile of the developer:** a risk neutral or risk averse developer may chose to go with the fixed design. However, a risk taking developer may wish to go with a flexible design. There may be a variety of reasons that leads a developer to be risk taking: a project of this nature may be a small asset in their portfolio and hence they may be willing to take certain risks with it, they may chose the flexible design in order to understand more about using such panels and employing manual labor. In the process, they may find other ways of improving the PLF or reducing costs and hence make the choice of flexibility more viable.

- **Information availability:** A developer with access to enough information could make a better case for a flexible design. The standard deviations associated with our input uncertainty was relatively high for the flexible cases and any more information a developer can acquire may reduce some of this deviation and provide them a better estimate of the distribution.

- **Sensitivity analysis and model limitations:** At the very outset of this report, we highlight the sensitivity analysis of certain underlying input parameters and then made the decision to focus on one of them (PLF). Our results could certainly vary if the other factors were included as well as uncertain distributions. This analysis is a representation of our inputs and assumptions hence should be evaluated keeping the same in mind. This project could certainly be further built on, both at the uncertainty distribution and flexibility design levels to provide an even more realistic understanding of the system and its levers.
8. Conclusion/ Lessons Learned

Although the fixed and flexible cases implemented in this project were accompanied by a diverse set of assumptions, it provided an extremely useful experience to understand some of the consequences of uncertainty, methods of classifying and analyzing uncertainty, and tools and options to implement flexibility in a system to possibly improve the expected value.

The project has provided the opportunity to learn some of the some concepts of the course, including the following:

- Recognizing and appreciating uncertainty in a system
- Analyzing the sensitivity of various underlying input parameters
- Modeling and creating distributions to classify uncertainty
- Analyzing methods to classify and incorporate uncertainty
- Understanding the value of flexibility in design and incorporating flexibility into existing systemic models
- Evaluating designs based on economic and mathematical indicators (NPV, IRR, P5, P95, etc.)

In particular, the class introduced us to three different methods of appreciating uncertainty – decision analysis, lattice models and simulations. Decision analysis is well suited for cases looking at 2-3 periods with discrete distributions where it is possible to calculate the value of information. Lattice models are most appropriate for cases with stationary uncertainty over multiple time periods but only taking one decision per analysis. Given the system that we were evaluating (non-discrete distribution over multiple time periods but with non-stationary uncertainty), neither of these methods would be appropriate in understanding the value of flexibility after incorporating uncertainty into the model. Given these limitations, we decided to use a simulation analysis for this project. A simulation analysis provides us the ability to create decision rules appropriate for this project and implement them over multiple time periods in an automated manner. Although this simulation provided a variety of challenges while being set up, it is extremely easy to use and build on once first established. Since we were not dealing with situations characterized by sudden changes or jumps or the stationary evolution of a variable, the simulation method provided the best all round approach to carry out this analysis.

Working on this project has provided me the tools and the mindset to evaluate systems level engineering problems from a perspective that isn’t necessarily traditional. Part of my reason to apply to the Technology and Policy Program at MIT was to gain an understanding of how to formally and mathematically deal with complex socio-economic and political systems. One of the characteristics of such systems is that they never have a correct answer! These systems are characterized by uncertainties of various kinds. For example, in my own research, uncertainty around energy policy plays a major role in influencing the way economic systems behave and how markets decide on energy technologies to proliferate. As shown in this class, it is naïve to assume one case over the other or to assume a mean of possible inputs while carrying out an
analysis on such a system. Success in dealing with such systems lies in the ability to understand
the variables that influence the system, understand the factors that influence such variables and
lead to uncertainty in them and hence design systems keeping in mind such uncertainty – this
beckons the need for flexible systems. I have thoroughly enjoyed this class as it allowed me to
carry out concrete analysis in the field of engineering systems and appreciate the complex
nature of the same. I hope to take forward the lessons of this class and influence the larger
community that value always doesn’t lie in picking one number over another but in appreciating
the limitations and uncertainties in systems that characterize today’s challenges.
Bibliography

