Dynamic energy analysis to assess maximum growth rates in developing power generation capacity: case study of India

Jyotirmay Mathur\textsuperscript{a,*}, Narendra Kumar Bansal\textsuperscript{b}, Hermann-Joseph Wagner\textsuperscript{c}

\textsuperscript{a}Mechanical Engineering Department, Malaviya Regional Engineering College, Jawahar Lal Nehru Marg, Jaipur, Rajasthan 302017, India
\textsuperscript{b}Centre for Energy Studies, Indian Institute of Technology, New Delhi 110016, India
\textsuperscript{c}Institute for Ecology and Environment, University of Essen, 45117 Essen, Germany

Abstract

Static energy analysis of power generation systems has been very much useful for assessing utility of systems in terms of energy input and output over their lifetime. A method of extending such analysis to cover dynamic implications of energy input and output has been established and demonstrated through this work. The methodology establishes a dynamic balance between energy input as cumulative energy demand for building new systems and output from available power plants that puts a limit on rate of building new plants. Separate analysis of different technologies in Indian context reveals that this maximum growth rate can be as low as 7.24\% for mono-crystalline photovoltaic systems and as high as 216.7\% for small wind energy systems.

Keywords: Energy analysis; Power generation; Dynamic energy planning

1. Introduction

As per the International Federation of Institutes for Advanced Studies (IFIAS) the term energy analysis means ‘the determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions or applying the information so obtained. Such analysis yields important life cycle parameters related to analysed systems such as energy yield ratio and energy pay back period. These parameters establish the utility of any system in terms of energy input and output similar to financial utility in terms of monetary input and output. Limitation with such analysis is that the results are helpful only in establishing utility of any system or for comparing two or more systems on the basis of energetics. However, decisions in real life situation and decisions in most energy planning exercises are taken on the basis of economic aspects and there is no established method for use of results of energy analysis into the exercise of energy planning. Authors have tried to develop a methodology for linking results of energy analysis with the conventional energy planning approach.

Many energy analysis studies have been conducted worldwide for various types of power generation technologies. Though focus of such studies has mainly been towards renewable energy bases systems, studies of conventional systems such as coal power plants have also yielded useful results. Hagedorn (1989) had analysed the energy input-output details and found the energy payback and yield of PV systems under different conditions of the manufacturing system. Later, in addition to the energy analysis, environmental implications were also included in studies conducted for various power-generating systems. Schaefer et al. (1992) and Kato et al. (1998) are some prominent studies covering the lifecycle analysis of PV systems. Besides studying the PV cells, modules studies were extended to cover all the peripherals related to PV plants in studies like Kohake et al. (1997). Similar to the analysis of PV systems, solar thermal systems were also analysed by numerous researchers. Mathur and Bansal (2001) have done energy analysis of five different types of solar water heating systems in six climatic zones of India. Wagner et al. (1995) had done energy and emission balance of solar water heating system in Germany. Wagner et al. (1995) later have done energy and environmental
analysis of different types of solar thermal systems used for different purposes in Germany. The Danish Wind Turbine Manufacturers Association had the analysis of different wind machines done for them in different operating situations including off-shore installations (Krohn, 1997). Energetics of three types of wind energy systems with different hub-heights and demographic conditions were studied by Pick (1998). Similar to the study of environmental analysis of PV systems, energy and environmental analysis (for greenhouse effect) was done by Mathur et al. (2002). Some conventional power plants were also analysed under the framework of energy analysis. Analysis of a modern coal thermal power plant was done by Heithoff et al. (1998) to find the energy requirement at different stages in addition to the operating stage. Analysis of a single type of power plants were extended for replacement of conventional systems by renewable energy systems to assess the relative potential of conservation of primary energy resources. In one such work, Wagner and Bansal (1998) and subsequently Guerzenich et al. (1999) have analysed wind energy, photovoltaic and solar water heating systems for India and Germany. The practice of carrying out energy analysis and utilisation of its results has been explained in many publications such as Mathur and Bansal (2001) and Guerzenich et al. (1999). In conventional energy analysis, results related to cumulative energy demand and energy yield ratio are analysed without considering the time frame into account as equations for such analysis are not having any transient term. The new approach presented in this paper enhances the widely accepted 'static' energy analysis to 'dynamic' energy analysis for utilisation of results of static and dynamic analysis into macro-level energy planning process.

2. Concept and methodology of dynamic energy analysis

The term cumulative energy demand (CED) for a certain power plant indicates load on primary energy resources through consumption of different forms of physical energy like electricity, fossil fuel, etc. The physical energy required to build any power plant obviously comes out of the pool of gross physical energy available for total consumption within the country/region/province under consideration. Thus, the gross demand can be split into two segments. One, energy demand as CED of different power plants and second one being the remaining demand for all other sectors of economy. The total requirement of energy (EDM) for capacity expansion at any point of time 't' depends upon the number and nature of plants being built up, which can be found using the following formula:

\[ EDM\text{(CONST)}_k = n_{k,t} \cdot CED_k \]

where \( EDM(CONST)_k \) is the physical energy required for construction of \( n \) plants of technology \( k \) at time \( t \); \( CED_k \) is the cumulative energy demand of each plant of technology \( k \).

The total energy demand for construction of different types of plants using different technologies can then be found through

\[ EDM\text{TOTAL}_t = EDM_t \]

Due to the gestation/construction period or time required for construction of power plants, the construction activity has to be started ahead of the time in which it is required for utilisation. For an exponential growth pattern, the number of plants of a certain technology \( k \), at any point of time \( t \), can be found from:

\[ n_{k,t} = \frac{n_{k,0}e^{a(t-t_c)}}{1-e^{-a(t-t_c)}} \]  \hspace{1cm} (1.4)

where \( n_{k,0} \) is the number of functional/operating plants at point of time \( t \), \( t_0 \) the number of functional/operating plants at time \( t = 0 \), \( t \), the construction time for each plant and \( a \) the factor for growth rate.

It can be understood that the total number of plants likely to be operational at time \( t' = t \) shall contain additional new plants whose construction has to be started at time \( t' = t \) or in other words, \( t' \) years before their operational requirement. Thus number of plants going under construction at time \( t' = t \) can be found by obtaining the difference between the number of operational plants at time \( t' = t \) and \( t' = t+\Delta t \) using Eq. (1.4) for these two different points of time:

\[ n_{k,t'} = n_{k,t} - n_{k,t+\Delta t} \]

\[ = n_{k,0}e^{a(t-t_c)} \]  \hspace{1cm} (1.5)

Total energy required for construction of plants of technology \( k \), at a point of time \( t \) is found using

\[ EDM\text{TOTAL}_t = CED_k \cdot n_{k,0}e^{a(t-t_c)} \]  \hspace{1cm} (1.6)

Total energy output from all operational plants of technology \( k \) can be found from

\[ EN_{k,t} = \eta n_{k,0}e^{a(t-t_c)} \]  \hspace{1cm} (1.7)
where \( EN_k; t \) is the total annual energy output from technology \( k \) at time \( t \) and \( \delta n_k \) the annual energy output from one plant of technology \( k \).

Therefore, availability of energy for satisfying active demand (demand other than CED), can be written as

\[
EN_{\Delta{\text{ACTIV}}}; t = \sum_k EN_k; t - \sum_k EDM_k(CONST); k; t, \delta 1.8 \delta
\]

where \( EN_{\Delta{\text{ACTIV}}}; t \) is the active demand of energy (demand other than CED) at point of time \( t \).

Requirement of this active demand of energy should be satisfied by the combination of all technologies for a self-sustainable growth of power-generation capacity. As is clear from equations of dynamic analysis, value of maximum growth rate for any technology depends upon the CED and the annual energy output.

Feasible solutions of Eq. (1.8) through Eqs. (1.6) and (1.7) are bound by the upper limit of growth factor \( \alpha \). This means that there is finite maximum value of growth factor \( \alpha \) for the equation of balance between demand and supply. It is because a growth rate higher than the maximum value suggested by the balance equation would result in disturbance of the dynamic balance between energy demand and supply causing creation of an energy sink instead of an energy pool. This situation is similar to the economic input-output balance for any self-sustaining enterprise in which not more than a certain rate of growth is possible, as considerable part of the earnings is required to meet essential expenses other than expansion.

3. Linking energy analysis with energy planning

Energy planning exercises, conventionally, take maximum growth rate as a user-defined optional constraint in the model. This constraint is usually a time series parameter, the value of which may be different for each period of study in case of each technology. It can be expressed in terms of units of plant capacity (GW in this case) or in terms of maximum allowed investment expressed in monetary terms or even in terms of percentage of capacity in use at any period.

The value of a maximum self-sustaining growth rate obtained by the approach discussed in the previous section can thus be used in energy planning as a constraint. This upper bound on growth is to be adhered even if the affordable growth rate based on other constraints like infrastructure support, fuel availability, etc. is higher than the former growth rate suggested by dynamic energy analysis.

Use of maximum growth rate individually for different technologies obtained from the dynamic analysis in energy planning would thus integrate the two different analyses. The benefit of linking or integrating both analyses is that instead of relatively less mathematical and less scientifically supported value of growth constraint, we have a more logical and scientifically obtained value of constraint. The former may be based upon non-tangible factors and may involve high and unknown degree of uncertainty; however, in the new approach, parameters are tangible and uncertainties can also be estimated to a large extent.

In the process of linking of output of energy analysis with energy planning, two different scenarios have been made to have a feel of possible variation in the final results. These scenarios have been explained below as Case 1 and Case 2.

Case 1: In this case maximum growth rate is found corresponding to a situation where energy demanded for building a new capacity of certain technology is equal to the energy supplied by the operational plants of the same technology. The hypothesis behind this condition is that expansion of capacity of each technology is a separate sub-program of the main capacity expansion program as they are individually governed by different bodies. Hence, each sub-program should be self-sustainable in itself without causing any extra burden on the other sub-programs of capacity expansion for other technologies. It is also assumed initially that in the final solution all the technologies are not observing their maximum growth levels. This assumption is justified due to the fact that the sum of capacities of various technologies corresponding to maximum growth rates obtained in this case, becomes much more than the total capacity required for the country. Therefore, it is quite obvious that less preferred technologies would be allocated a lesser growth rate in the solution, keeping the margin for supply of energy for the active demand. Assuming the condition when all the technologies are having maximum self-sustaining growth rate, in that situation despite having generation of considerable amount of energy, no energy would be available for consumption as active demand. Such a situation is unlikely to arise, as aggregate effect of different growth rates of different technologies is much higher than the aggregate growth of energy demand.

Therefore, for the case of a self-sustaining capacity expansion program, expressions on the right-hand side of Eqs. (1.6) and (1.7) must balance. If the energy demand for construction (Eq. (1.6)) is more than the energy output (from Eq. (1.7)), the program of capacity expansion becomes a net energy sink rather than serving the purpose of source of energy for other activities. The limiting condition for each technology \( k \), can be expressed as

\[
(\delta n_k) \delta_\alpha e^{\alpha t - \alpha t} \geq CED_k \delta n_k \delta_\alpha e^{\alpha t} e^{-\delta t c}, \tag{1.9}
\]

For the above equation, maximum value of growth factor \( \alpha \), can thus be obtained by rewriting the above inequality for limiting condition in the following form
and solving it for maximum value of ‘a’: 
\[
\frac{em_k}{CED_k} = r_{en} - \frac{1}{1 - e^{-rtc_k}} 
\]

**Case 2:** Instead of making all the sub-programs for all the technologies self-sustainable individually, another approach for planning may be by making compulsory for each sub-program to contribute towards the national energy demand besides taking care of its own expansion. Meaning, self-sustaining is not the sufficient condition for each sub-program but it has to contribute towards the remaining part of the national demand also. This approach is in contrast to the previous case, where there may not be any net contribution from a fast growing technology. Due to the most common objective function of energy planning, i.e. minimising the total system cost, the cheapest technology (having least discounted total cost) is likely to get more growth as compared to the costlier ones. Consequently as per case 1, the limiting condition would arise for cheaper technologies but not for the costlier ones and utilisation of cheaper technologies will be more than the case 2. Hence, the overall system cost in case 2 would be higher than the first case. In this case, only one part of the gross annual energy output from each technology is considered for reinvestment for construction of new plants for capacity expansion. This factor of permissible reinvestment, named as ‘reinvestment factor’ in this work, can be the same for all technologies or different for each technology, depending upon the promotional priorities. In this study, a common factor for all the technologies has been considered for this purpose. A typical common factor can be found from the share of total CED in the gross energy demand in the base year. An underlying assumption while using this factor is that the same proportion of energy can be spared from the energy pool, for capacity expansion in all the periods. It would be worth mentioning here that if any particular technology is to be promoted, it can be assigned a lower reinvestment factor, other than the general common factor. It would result in a higher limit of maximum growth rate for that particular technology. On the other hand, if any technology is to be suppressed, a higher reinvestment factor can be assigned. This factor thus acts similar to financial subsidy for technologies that are to be promoted.

The balance of energy input and output with reinvestment factor V can be then expressed as
\[
\left[(em_k)n_0e^{\alpha x} - \omega_C\right] \geq \sum_k \text{Output}_k 
\]

where, \(x\) is the factor representing percentage of energy output from that can be used for capacity expansion instead reinvesting the entire output for the purpose.

This approach will definitely yield a lower value of maximum growth rate for capacity expansion for each technology that can be obtained by rewriting the above equation in the following form and solving it for maximum value of growth factor ‘a’:
\[
\frac{x en_k}{CED_k} = \left[e^{\alpha x} - 1\right]. 
\]

Since, the energy re-investment factor ‘x’ has a potential of affecting the growth factor V by a large extent, a judicious decision about ‘x’ is necessary for making the results of the analysis more feasible and useful. This factor has been estimated by two methods. One method has been through an analogy between financial and energy sectors. The factor representing percentage of national budget allocation for power generation capacity expansion has been used to represent the amount of energy re-investment from the total energy pool. Another approach for finding the factor ‘x’, is through the CED values for different power plants and using Eq. (1.13). The numerator of this equation is found by summing up the product of new installed capacity of each technology \((CAP_{fj})\) at time ‘f’ and the specific CED of that technology to obtain the total energy used for capacity expansion. The denominator is summation of power output from all technologies. Their ratio gives the fraction of gross energy production in the country that is used for installing new capacity.
\[
x = \frac{\sum_k \text{SPCED}_k \cdot \text{CAP}_{fj}}{\sum_k \text{Output}_k}, 
\]

where, \(\text{SPCED}_k\) is the CED for unit capacity of technology \(k\), \(\text{CAP}_{fj}\) is the new installed capacity of technology \(k\) and \(\text{Output}_k\) the total power output from technology \(k\).

This approach finds the percentage of energy re-investment in the base year, thus de-coupling the energy demand for new plants from active demand of energy, i.e. national energy demand excluding demand as CED for different plants.

Solving Eq. (1.10) for maximum value growth rate \(a_{\text{max}}\), we get the following expression for each technology \(k\), in case 1:
\[
a_{\text{max}, k} = \frac{\ln\left[en_k = \text{CED}_k + 1\right]}{tc_k} 
\]

and similarly, using Eq. (1.11), maximum growth rate for each technology \(k\), in case 2 can be calculated by
\[
a_{\text{max}, k} = \frac{\ln\left(x \cdot en_k = \text{CED}_k + 1\right)}{tc_k} 
\]

Reduction in maximum growth rate of each technology is clearly visible due to an additional term ‘x’ appearing in the logarithmic expression value of which is always less than one.
4. Use of developed algorithm

As mentioned earlier, the most important input for conducting and using dynamic energy analysis in energy planning is the CED. International Energy Agency has published range of LCA parameters of different power generation technologies in one research report on hydropower (IEA, 2000). This study presents energy yield ratios of various technologies for different part of the world including Asia. Results related to energy yield ratio, in this study have been found in agreement with the results found in by our own calculations. Besides, in one study of photovoltaic power generation in Germany, a comprehensive coverage of accumulated energy in different power plants was presented covering power plants of various technologies and plant sizes (Schaefer, 1992). Values of CED found through our own study match with the values mentioned in this study and hence for other plants values of CED have been taken from this work for calculations of dynamic analysis. Some of the referred studies have even given the share of various fuels in the total CED. In the case of PV power plants, the share of electricity has been found to vary from nearly 70% (Schaefer, 1992) to about 90% (Vollmecke, 2000). The share of electricity in wind energy converters has been found to be about 30%. In the case of coal power plant, this share is quoted to be about 25% (Heithoff, 1998). Table 1 presents the range of CED related information found and calculated through these studies. Few other studies like Vollmecke (2000) and Krohn (1997) were also consulted and found to be in tune with other studies taken as references. The last column indicates the values chosen for use in the dynamic analysis calculations done in the next section of this chapter. These values have been taken corresponding to the preferred plant sizes in India and therefore do not have any fixed co-relation with the range of CED. However, sensitivity analysis has been done to find the effect of variation in CED on results of dynamic analysis. Values given in Table 1 are also rounded off from exact values as mentioned in parent studies because these are only to represent the range of CED.

5. Calculation of maximum growth rates

Results of energy analysis, as summarized in Table 1 have been extended to find maximum allowable growth rate for each considered technology. In the methodology, the method of calculating maximum growth rate using the new developed dynamic analysis approach has been explained for both the cases. One, named as case 1, in which the entire energy output from any technology can be reinvested for capacity expansion if it is the most preferred technology. In the other case, called case 2, only a fraction of energy output is considered for reinvestment for capacity expansion as in India, each set of technologies is managed by a separate ministry or department. In the past planning periods, the power sector has been allocated about 20% of the total planned public sector outlay for power generation capacity expansion. Following the same approach, a maximum of 20% of the national power output has been considered for reinvestment for capacity expansion and this ceiling has been uniformly applied on each technology. It means, a maximum 20% of the power output in any year from every technology has been kept in transient equations to find the maximum growth rate of each technology. Investigation of Eq. (1.12) shows that CED, annual energy output $e_n$, and construction time $t_c$ (gestation period) of power plants are the main governing parameters for determining the maximum growth rate $V$ besides the reinvestment factor $x$.

Table 2, shows the maximum growth rate corresponding to average construction time for each plant for cases 1 and 2 along with the values of other related parameters as mentioned above.

There is a difference in the values of CED given in Table 1 with the values given in Table 2. It is

<table>
<thead>
<tr>
<th>Technology</th>
<th>CED$_{max}$ (MWh/MW)</th>
<th>CED$_{min}$ (MWh/MW)</th>
<th>CED$_{chosen}$ (MWh/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaïc (mono-crystalline)</td>
<td>20,500</td>
<td>10,000</td>
<td>12,500</td>
</tr>
<tr>
<td>Photovoltaïc (poly-crystalline)</td>
<td>20,000</td>
<td>8000</td>
<td>9500</td>
</tr>
<tr>
<td>Photovoltaïc (amorphous)</td>
<td>13,300</td>
<td>5000</td>
<td>6500</td>
</tr>
<tr>
<td>Wind (small)</td>
<td>4700</td>
<td>2000</td>
<td>2500</td>
</tr>
<tr>
<td>Wind (large)</td>
<td>2600</td>
<td>1000</td>
<td>1500</td>
</tr>
<tr>
<td>Hydro (large)</td>
<td>10,000</td>
<td>3500</td>
<td>6500</td>
</tr>
<tr>
<td>Hydro (small)</td>
<td>10,000</td>
<td>3500</td>
<td>6000</td>
</tr>
<tr>
<td>Coal (advanced)</td>
<td>4000</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Coal (moderate)</td>
<td>3000</td>
<td>800</td>
<td>1000</td>
</tr>
<tr>
<td>Coal (basic)</td>
<td>2500</td>
<td>600</td>
<td>800</td>
</tr>
<tr>
<td>Natural gas (combined cycle)</td>
<td>3000</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td>Natural gas (simple cycle)</td>
<td>2000</td>
<td>400</td>
<td>500</td>
</tr>
</tbody>
</table>
Table 2

Maximum growth rates obtained through dynamic energy analysis

<table>
<thead>
<tr>
<th>Technology</th>
<th>CED&lt;sub&gt;electrical&lt;/sub&gt; (GJ/MW)</th>
<th>Annual output (GJ&lt;sub&gt;el&lt;/sub&gt;/MW)</th>
<th>Average plant construction time (years)</th>
<th>Maximum growth rate (case 1) (%)</th>
<th>Maximum growth rate with 20% re-investment factor (case 2) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic (mono-crystalline)</td>
<td>36,000</td>
<td>4730</td>
<td>1</td>
<td>31.9</td>
<td>7.24</td>
</tr>
<tr>
<td>Photovoltaic (poly-crystalline)</td>
<td>27,360</td>
<td>4730</td>
<td>1</td>
<td>40.2</td>
<td>9.42</td>
</tr>
<tr>
<td>Photovoltaic (amorphous)</td>
<td>18,720</td>
<td>4730</td>
<td>1</td>
<td>54.3</td>
<td>13.5</td>
</tr>
<tr>
<td>Wind (small)</td>
<td>2700</td>
<td>12,614</td>
<td>0.6</td>
<td>444</td>
<td>216.7</td>
</tr>
<tr>
<td>Wind (large)</td>
<td>1620</td>
<td>12,614</td>
<td>1</td>
<td>314.6</td>
<td>169.6</td>
</tr>
<tr>
<td>Hydro (large)</td>
<td>11,700</td>
<td>18,921</td>
<td>7</td>
<td>24.7</td>
<td>9.35</td>
</tr>
<tr>
<td>Hydro (small)</td>
<td>10,800</td>
<td>23,652</td>
<td>3</td>
<td>64.1</td>
<td>25.8</td>
</tr>
<tr>
<td>Coal (advanced)</td>
<td>2160</td>
<td>20,183</td>
<td>4</td>
<td>83.0</td>
<td>46.2</td>
</tr>
<tr>
<td>Coal (moderate)</td>
<td>1800</td>
<td>20,183</td>
<td>4</td>
<td>87.4</td>
<td>50.1</td>
</tr>
<tr>
<td>Coal (basic)</td>
<td>1440</td>
<td>20,183</td>
<td>4</td>
<td>92.9</td>
<td>54.9</td>
</tr>
<tr>
<td>Natural gas (combined cycle)</td>
<td>1620</td>
<td>20,183</td>
<td>3</td>
<td>120</td>
<td>69.8</td>
</tr>
<tr>
<td>Natural gas (simple cycle)</td>
<td>900</td>
<td>20,183</td>
<td>2</td>
<td>208.8</td>
<td>131.3</td>
</tr>
</tbody>
</table>

due to the fact that for the purpose of dynamic analysis, the share of electricity alone in the CED was of use as the developed algorithm of dynamic balance is for the supply and demand of electricity only, not for total energy demand and supply which also includes other forms of energy. For this purpose CED<sub>electric</sub> was converted into CED<sub>electrical</sub> using the information given in relevant literature.

6. Discussion and conclusions

The developed method provides a reasonably good basis for drawing dynamic interpretations from the results of energy analysis that often is ended with providing static results in the form of energy yield ratio and energy payback period. It gives an important input for the task of energy planners in the form of maximum growth rate. A very broad range of results in the form of maximum growth rate, 7.24% in case of mono-crystalline photovoltaic systems to 216.7% in case of small wind energy systems itself establishes the importance of such analysis. From these results, one may observe the change from country to country due to change in the share of electricity in total cumulative energy demand. A similar effect may also occur due to any other factor such as plant size that either affects the CED<sub>electrical</sub> or the construction time of the plant or annual power output from the plant in its useful life. However, results obtained by the algorithm developed are accurate enough to provide guidance for energy planning, specially while planning and devising special schemes for promotion of any particular type of power generation technology such as photovoltaic systems.

References


Völlmeck, S., 2000. Kumulierter Energieaufwand ausgewählter Herstellungsprozesse der Photovoltaik; Studienarbeit at Ökologisch Verträgliche Energiewirtschaft (Diplom Thesis in German), Universität GH Essen, Germany.
