SOLAR ENERGY -- THE GLOBAL ALTERNATIVE[1]

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1. Introduction

It was the best of times ...

Stone-breaker

Top-down and Bottom-up

2. Bottom-up Approaches

2.1 Karnataka DEFENDUS Near-Term (2000) Electricity Scenario

- ≈ 40% of the energy requirement and installed capacity of conventional projection
- Development Focus (more energy services for the poor) + Efficiency Improvements and Carrier Substitution
- Least-Cost Mix (EI & CS + Decentralized Renewables + Cleaner Centralized)

2.2 PG&E Medium-Term (2030) Electricity Scenario

- Least-Cost Mix (EI + Decentralized Renewables + Clean Centralized/ Advanced Natural Gas)

2.3 India Medium-Term Oil Strategy

- Road --> Rail Freight Shift
- Kerosene Lamps --> Electric Illumination Shift
- Kerosene --> LPG Cooking Shift

3. Top-down Approaches

3.1 ENSWORLD 2020 Global Scenario

- ?? % of IIASA Low Scenario
- South-North Convergence
- Dramatic Improvement in Energy Services in LDCs

3.2 Renewable Energy Long-Term 2050 Scenario

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3.3 Renewables against Global Warming

3.3.1 Global Warming and Greenhouse Gas Emissions

Human activities are now thought to have the potential to alter significantly the Earth's climate on a global scale. This potential derives from increasing atmospheric concentrations of greenhouse gases (GHGs) which are predicted to warm the earth's lower atmosphere and surface by reducing the efficiency with which it cools to space. The most important GHGs are water vapor, carbon dioxide, methane, nitrous oxide, halocarbons (e.g., the chlorofluoro-carbons), and upper-tropospheric and lower-stratospheric ozone.

The two primary sources of the observed increase in atmospheric carbon dioxide are combustion of fossil fuels and land-use changes (primarily deforestation) accounting for approximately three-quarters and one-quarter respectively.

A key issue is to relate emissions of GHGs and their precursors to future concentrations of GHGs in order to assess their impact on the radiative balance and thereby the Earth's climate. A number of different types of carbon cycle and tropospheric chemistry models have been developed for this purpose. However, it should be noted that all carbon cycle models are subject to considerable uncertainty.

It is, clear, however, that if present trends persist, it is very likely that the resulting impacts on the global atmosphere will lead eventually to changes of the global climate that would seriously perturb human societies and perhaps even endanger human life. Further, the response time of the climate system is such that, by the time significant changes are detected, it may be too late to rectify the situation.

This is why many countries are committed to putting precautionary policies in place, of which the GEF is a part. The idea is that, as further evidence on global warming and its consequences is gathered, the investments of the GEF will leave the international community better placed to reduce GHG accumulations to safe levels, over the long term, should the need arise. The approach is equivalent to an insurance policy. The various measures (technologies, practices) and policies that the GEF should support are those that would need to be turned to on a large scale if it becomes certain that GHG accumulations have to be restricted appreciably.

A distinction must be made between the objective of reduction of net GHG emissions and the objective of stabilization of GHG accumulations. By focussing only on the reduction of, for example, CO_2 emissions, the global warming problem would only have been delayed by a decade or two, but would have been substantially unaddressed. Delaying global warming is not the same as preventing it. The reduction of net emissions is a necessary step, but not sufficient; in addition, the magnitude of reduction should be sufficient to achieve the stabilization, if not reduction, of GHG accumulations in the atmosphere at some safe level over the long term. Thus, the effectiveness of interventions cannot be divorced from objectives and benefits cannot be separated from targets. However, virtually all these interventions involve investments and therefore there has to be strategy for reducing net GHG emissions into the atmosphere.

3.3.2 Least-Cost Emissions-reduction Planning -- the Ideal Approach

With respect to its energy-related investments, the primary function of the Global Environmental Facility (GEF) is to develop cost-effective approaches towards addressing the global warming problem. Investments should be directed towards that mix of technologies[3] which can achieve the maximum reduction in emissions for a given investment. The identification of such a mix requires information on the unit cost of emissions reduction for the various technologies and the magnitude of the emissions reduction achievable with these technologies.

If this information were available, one could adopt a least-cost emissions-reduction strategy based on cost-emissions-reduction-technology (CERT) curves. These curves are constructed (cf. Appendix 1) by choosing the technology with the lowest unit cost of emissions reduction as the first element of the mix, exploiting its emissions reduction potential, choosing the next most expensive technology as the second element of the mix, and so on until the desired emissions reduction target is achieved. Thus, one can either estimate the total investment that is required for the mix of technologies to achieve a given magnitude of emissions reduction or one can identify which mix of technologies is likely to achieve the maximum emissions reduction for a given total investment.

Least-cost-emissions planning is a worthwhile approach to move towards, for several important reasons:

- it takes into account both the cost-effectiveness of a technology in reducing greenhouse gas (GHG) emissions as well the potential impact of that technology with regard to emissions-reduction;
- it treats the supply-side and demand-side options for reducing GHG emissions on equal terms and does not discriminate against either of them;
- it ensures that different technologies are compared and prioritized on the basis of their cost-effectiveness (unit costs and potential emissions-reduction);
- it provides some idea of how much reduction in emissions is achievable (say, in percentage terms) and what cost;
- it constitutes a powerful heuristic for developing an investment strategy and portfolio for reducing GHG emissions.

Unfortunately, least-cost emissions-reduction planning is easier recommended than implemented because of the many conceptual and methodological problems in computing the costs of interventions and in estimating the benefits or effectiveness. In the first place, there has to be an agreed methodology of computing the costs of an emissions-reduction technology, and in particular the incremental costs over and above the conventional technology. Also, there can significant reduction of net CO_2 emissions from energy production and use without there being a stabilization of carbon accumulations and a diminution of the threat of global warming. Thus, the benefits of a technology cannot be separated from objectives, for instance, whether the objective is reduction of net CO_2 emissions or stabilization of carbon accumulations.

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[3] The word "technologies" has been used here to be synonymous with "projects" in the sense that every project presumes a technology upon which it is based and every technology can be used to design a project around it.

In particular, there are a number of specific questions:

(1) how to allow for the prospective costs of GHG emissions (or of reducing them) when appraising GEF projects;
(2) what discount rate is appropriate to use in comparisons of costs, bearing in mind inter-generational concerns on the one hand and the importance of cost-effectiveness on the other;
(3) how to estimate the benefits of innovation, in particular the contribution of an investment to reductions in the costs of future investments when cost-curves (as a function of investment) are steep;
(4) how to reduce the large transactions costs in some types of GEF projects having good economic potential.

3.3.3 Costs of Stabilizing Carbon Accumulations

Consider the present situation (Figure 1a) in which carbon accumulations are rising over time due to the dependence on conventional fossil-fuel energy technologies. If a safe limit has to be set on the level of accumulations, then it would be necessary to switch eventually to non-fossil alternatives. Suppose, for heuristic purposes, the switch is assumed to take place at the time T in a step-function fashion (Figure 1b), then the marginal cost of energy consumption would change from the fossil-fuel value of "f" to that of the non-fossil fuel alternatives, "n". Then, the present value of the extra marginal cost at the time t = 0 is

$$c_0 = (n-f)(1+r)^{-T}$$

Thus, the actual marginal cost of fossil fuel consumption is $f_0 + c_0$ and c_0 is the shadow price or carbon tax necessary to bring about investment in the non-carbon alternatives.

The shadow price increases with time such that

$$c_t = c_0 (1+r)^t$$

but this increase can continue only until it equals the difference (n-f) between the marginal costs of the non-fossil fuel alternatives and the fossil fuels. Thereafter, the non-fossil fuel alternatives become the cheaper and chosen option.

Consider any activity (such as energy efficiency or use of a low-carbon emitting energy resource such as natural gas) that would delay the time at which the carbon accumulations constraint is reached so that the transition to non-fossil fuel alternatives is shifted from T to T + _T. As a result, the present value of the "delayed" marginal cost at the time t = 0 is

$$c_0' = (n-f)(1+r)^{-(T+\_T)}$$

which is related to the "undelayed" extra marginal cost c_0 thus:

$$[c_0'/c_0] = (1 + r)^{-–T)}$$

From this expression, it is seen that c_0' is less than or equal to c_0 depending upon whether $–T)$ is greater than or equal to zero. Thus, the term c_0' is the <u>shadow price</u> or marginal benefit to be attributed to "buying time" through measures such as energy efficiency, use of a low-carbon emitting energy resource such as natural gas, other emissions reduction measures and sequestration.

Incidentally, this elementary treatment shows that <u>the best strategy of addressing the problem of global warming is a two-pronged strategy of (1) "buying time" with technologies that delay global warming and (2) preventing global warming with non-fossil fuel technologies</u>. Since the first prong of the strategy (viz., energy efficiency, use of a low-carbon emitting energy source, other emissions reduction measures and sequestration) is effective only to a limited, albeit significant, extent, it is essential to back them with the second prong of non-fossil fuel alternatives which may therefore be called <u>backstop</u> technologies.

The step-function switch to non-fossil fuel alternatives is, however, an over-simplification because

- the time taken to switch to the non-fossil fuel alternatives in order to comply with the carbon emissions would be quite long
- the costs of the renewable energy alternatives are declining while in certain markets (particularly in the non-electric markets) the costs of fossil fuels may rise slowly over the long term.

As a result, the programme of introduction of non-fossil fuel alternatives would have to be brought forward to address the marginal increase in CO_2 emissions. In other words, the investments on these alternatives will have to be distributed over time. But how these investments are distributed over the future is a matter of estimating the scope for substituting renewable energy for fossil fuels.

Perhaps the best assumption is that the investments could be scaled up in proportion to the estimated output of renewables, N_t, in each period t of the duration T over which the program of renewable energy investments is phased in (roughly 50-70 years):

$$d_t = N_t / Ó (N_t)$$

For instance, if the d_ts sum up to about one-third in the first half of the program and two-thirds in the second, more investments would be devoted to the later phases when the renewable technologies are fully developed without starving the earlier phases of the program when the technologies have to be developed. An illustrative time profile of investment in the non-fossil fuel or backstop technologies during the phases in which they are being developed and substituted for fossil fuels is shown in Figure 2.

This time profile is essential for estimating the shadow prices to be placed on reducing carbon emissions, but in addition, it is necessary to know the prospective costs of the backstop technologies relative to those of fossil fuel.

A satisfactory portfolio cannot be determined without an analysis of how relative costs are changing. The most promising types of investments in renewable energy are still small scale, and costs are declining with investment and technical progress. The transactions costs of demonstrating and developing new approaches are also initially high. What is relevant for the GEF therefore is not only (1) their current cost, but (2) the prospects for reductions in costs of the technologies in question, and (3) the contribution that the GEF can make to cost reductions.

The costs of the backstop technologies relative to fossil fuels vary greatly with market and application. They also vary over time. For some applications, renewable energy is already the least-cost option, e.g., the use of biomass for cogeneration, of wind energy in favourable locations, and of photovoltaics for rural electrification and the provision of power in electricity distribution networks. But substituting renewable energy for fossil fuels on a large scale would likely raise costs. Table 2 presents an illustrative assessment of the long-term costs of using renewables for electric power on a large scale.

Table 2: Costs of Electricity Generation, US cents/Kwh (1990 prices)

SOURCE OF POWER	PRESENT	LONG-TERM EXPECTATIONS
Coal	4.5	May rise gradually with fuel prices
Oil	6.0	May rise gradually with fuel prices
Gas (combined cycle)	5.0	May rise gradually with fuel prices
Nuclear	5.0	Rises with environmental factors
Photovoltaics	30.0	7.0
Thermal-Solar	15.0	7.0
Biomass	15.0	4.0-6.0

There is growing consensus that, for electricity generation, the backstop technologies may eventually become competitive with fossil fuels, at least in the high insolation regions of the world. It is the provision of substitutes for solid, liquid and gaseous fuels (or non-electric energy) where the costs of the backstop technologies are highest. And, non-electric energy currently comprises 60% of the primary energy markets in the industrialized countries and over 65% in the developing countries. The main backstop technologies are biomass-derived fuels (ethanol and methanol), hydrogen (via electrolysis), or further electrification of the energy markets which will depend crucially on developments on storage technologies. Table 3 summarizes a recent assessment of costs.

Table 3: Costs of Oil Fuels & their Backstop Technologies (US 1990 $/boe)

OIL FUELS AND THEIR BACKSTOP TECHNOLOGIES	CURRENT	PROSPECTIVE/ LONG-TERM
Oil Fuels (ex-refinery)	25	40
Biomass (ethanol)	100	70
Hydrogen and Hydrides	200	150
Electrification	100	100

The effective costs to consumers of the electrification and hydrogen alternatives may eventually be lower than indicated in Table 3 for two reasons. The first is that the efficiency of electric motors powered by batteries and fuel cells is much greater than that of the internal combustion engine; it is potentially around 60% as compared with 20% in the latter. Second, they have other environmental advantages because there are no emissions of harmful gases (assuming the electricity supplies are eventually based on renewables). Biomass-derived energy is also land intensive and its production on a large scale would place great pressure on land resources; this would eventually raise costs and make electrification or the use of hydrogen more attractive, if only as a complement to biomass fuels. Nevertheless, it seems that (a) biomass-derived liquid fuels would be the main backstop technology for some time and (b) that whatever backstop technology is used eventually, and even allowing for the efficiency factor just mentioned, its costs would likely be higher than those of fossil fuels.

Since the shadow price, c_t, to be attached to carbon emissions is greater for the marginal backstop technologies than for the most promising non-marginal options[4], the question arises as to whether the higher or the lower shadow prices should be used. Here, the view is taken that the shadow prices should best based on the costs in the non-electric markets (Table 3) where the substitutes for fossil fuels are likely to be more expensive rather than in the electricity markets (Table 2) where the renewable energy options have good prospects of becoming competitive with fossil (and nuclear) fuels in the long-term.

The logic underlying this view is that the more promising of the backstop technologies whose costs would be less than $f_0 + c_{0,m}$ would then be given added weight when the present value of the costs are compared. At the same time, some marginal technologies with costs close to $f_0 + c_{0,m}$ would not be excluded; only the outliers would be left out, pending further developments. Further, those applications of the backstop technologies that can be identified as having costs lower than f_0 in the so-called "niche"

[4] If the shadow prices to be attached to the carbon emissions from the marginal and non-marginal technologies are $c_{0,m}$ and $c_{0,nm}$, their difference is given by $c_{0,m} - c_{0,nm} = (n_m - n_{nm})(1+r)^{-T}$.

markets, would have the highest returns. Using the cost estimates of Table 3, the estimates of shadow prices to be placed on carbon emissions are shown in Figure 3.

Until more reliable estimates of costs are available, a reasonable basis for cost-effectiveness studies might be to take a rounded value of c_0 = $35/tonne of carbon rising at 10% per year up to a limit of about $600 per tonne. Alternatively, if all comparisons of costs are made in present value terms at t = 0, a constant undiscounted figure of $35/tonne might be used.

3.3.4 The Reflection of International and Inter-generational Concerns

Two rules might usefully be followed to best reflect in GEF policies the international and inter-generational concerns about global warming.

The first is to base the GEF portfolio on the types of investments that would most likely be needed in a "worst-case" scenario of global warming. "Middle-of-the road" scenarios are not relevant for GEF for two reasons. First, they ignore the asymmetry of the risks and the point that what eventually might happen, in the absence of appropriate policies, could be much worse than projected. The idea of a precautionary policy, like insurance policies, is to prepare for "worst-case" scenarios. Second, given the ambiguities in the evidence in the possible extent and consequences of climate change, and that some relationships (e.g., ocean-climate interactions and ocean currents) have not been modelled and estimated in a way that has been universally accepted, it is necessary to pay as much attention to the variance as to the expected value of the independent variable. This too argues for a "worst-case" scenario.

The GEF, therefore, must be part of a precautionary policy in which the aim is to leave the international community better placed to respond to the "worst-case" global warming problem should the need arise. If its investments are based on a seemingly 'risk-neutral' position or a 'most likely' outcome, this would be to work against the purpose of the GEF, which is to prepare for contingencies. It follows that GEF's own investments should support the development of the various technologies and practices that would have to be turned to a large scale in event of global warming requiring fundamental changes in policy.

The second is to base GEF decisions on a carbon accumulations constraint of the form derived in Section 8 to provide preliminary estimates of costs (the shadow price to be placed on carbon emissions). Introducing a carbon accumulations constraint into the analysis of energy investments amounts to using the resource depletion rule often used in the past for fossil fuels. The rule has become discredited in recent years, because each time a limit to reserves was thought to be approaching, the limit was extended by new discoveries (there is a moral to this). In the context of global warming, the resource in question is not the availability of fossil fuels but the safety margin. This safety margin (defined by the limit to the use of fossil fuels set by concerns about climate change) can be deemed to be a resource because it is used up or depleted with increase in GHG accumulations.

If a limit is set to the use of fossil fuels, not by their availability, but by the amount of carbon the atmosphere can safely absorb, the imputed cost (or shadow price) of using them grows at a rate equal to the discount rate until the limit is reached and they can be replaced by non-net-carbon-emitting or backstop technologies. This means that the shadow price to be attached to carbon savings is undiscounted in NPV comparisons of costs, at least up to the point where the backstop technologies are widely deployed.

The main point about the rule is that it gives an appropriate weight to those options that are consistent with stabilizing (or even reducing) carbon accumulations over the long term. Interestingly, it also means that in NPV comparisons of costs the shadow price on carbon emissions is then undiscounted over time, since its value rises according to a compound-interest law involving the discount rate.

3.3.5 Uncertainties and Risks

There is no certainty, even within broad limits, regarding either the extent, likelihood or consequences of climate change. This does not, however, lead to arbitrary ground rules for decision-making. Consider the risks at two levels: climate change, and for the energy industry.

Suppose the absorptive capacity of the atmosphere were greater than is implied by the scenarios used in the above calculations, which are based on a fairly rapid development of the renewable energy alternative. If the time at which the carbon accumulation's limit is reached were to be delayed by a decade, the shadow price for the imputed carbon tax) would decline to about 40% relative to the initial value (of $35/tonne) calculated above; conversely, it would rise to about 2.6 times the initial value if the limit were advanced by a decade[5].

Decisions as to whether to raise or lower the shadow price must ultimately depend on the findings of current and future research on climate change. (The same would apply to developments in the backstop technologies which may justify the initial estimates being raised or lowered.) The important point is to pursue a policy which keeps options open so that the shadow price can be raised or lowered relative to the path initially agreed upon depending on the findings of climate research and energy R & D.

The risks to the industries supported by the GEF should not be large. It is likely to be some time (perhaps more than a decade) before the findings of climate research might establish what the GHG accumulations limit is likely to be, and thus before the ground rules could justifiably be changed because of shifts in the perceived limit. There would thus be some continuity in policy. If the global warming problem proves to be less serious than, say, the projections of the IPCC, developments in technologies that already have useful market outlets would have been stimulated, albeit on a larger scale than would ideally have been required.

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[5] From $[c_0'/c_0] = (1+r)^{-\Delta T)}$, it follows that $[c_0'/c_0]$ is 0.39 if r=10% and ΔT= +10 years, and $[c_0'/c_0]$ is 2.59 if r=10% and ΔT= -10 years.

3.3.6 Assigning a Cost (or Shadow Price) to GHG Emissions

A vital step in assessing the cost-effectiveness of technologies is estimating the cost (or shadow price) of GHG emissions. The shadow price needs to be based on an accumulations constraint rather than on an annual emissions limit. Though it is not known with certainty and consensus what is the safe level at which carbon and other GHG accumulations should be stabilized, it turns out that, unless a 'runaway' feedback occurs, use of the backstop technologies is consistent with stabilizing accumulations at any one of several levels over the long term. Thus, the ground rules derived are not too sensitive to the magnitude of the safe level.

It is proposed that, for GEF projects, the cost (or shadow price) of GHG emissions should be the extra marginal cost of turning to non-GHG-emitting or backstop technologies, i.e., the marginal costs of renewable energy technologies should set upper bounds to the shadow price (or imputed tax) to be placed on GHG emissions. This means that the shadow price grows at a rate determined by the discount rate until the long-term costs of using the backstop technologies is reached.

The resulting formula for estimating the marginal cost is similar to that for computing the optimal price of a depletable resource. According to the depletable resource formula, the price of a resource (such as fossil fuels) equals the "extraction cost" plus a "user cost" term which rises over time until the backstop or replacement technology (renewable energy) becomes economical. In the context of global warming, the resource in question is not the availability of fossil fuels but the safety margin. This safety margin (defined by the limit to the use of fossil fuels set by concerns about climate change) can be deemed to be a resource because it is used up or depleted with increase in GHG accumulations.

It is vital that the upper bounds of the shadow price should be set by the costs of the marginal technologies likely to be brought into use -- not by the lowest costs of the most promising technologies. With this approach, technologies at the margin, and of course those below it, automatically qualify; only outliers do not. Further, extra weight is given under this criterion to those applications (such as the use of photovoltaics for rural electrification in favorable locations) which reduce any added costs of turning to renewables.

The preliminary estimates suggest a figure of about $35/tonne of CO_2 rising at the discount rate of 10% per year up to $600/tonne. Alternatively, an undiscounted figure of $35/tonne might be used in NPV calculations of costs. Such estimates should be raised or lowered periodically as further evidence on costs is gathered. They would also eventually be raised or lowered according to the emerging evidence on global warming.

3.3.7 Two-pronged Precautionary Strategy

With respect to the global warming problem, the GEF should be part of a precautionary policy. Its aim should be to support those activities and investments that would leave the international community better placed to address the global warming problem, should the need arise. Hence, the investments and activities it supports should be based on the premise that global warming will take place.

In a global warming scenario, the achievement of energy efficiency must be an important element of the policy of reducing CO_2 emissions. But, however economically desirable energy efficiency may be, it will not by itself prevent carbon from accumulating in the atmosphere. Global warming could be delayed by energy efficiency, but it can be prevented only by widespread recourse to the non-net-carbon-emitting or backstop technologies, the most promising of which are renewables.

Thus, the best strategy of addressing the problem of global warming is a two-pronged strategy of

(1) "buying time" with technologies that delay global warming
(2) preventing global warming with non-fossil fuel or backstop technologies.

Buying time is best done through energy efficiency, environmentally more benign fossil fuel technologies (such as natural gas) and emissions reduction and GHG sequestration. And, the most promising non-fossil-fuel or backstop technologies are those using renewable energy, primarily solar and biomass, the costs of which have declined appreciably over the past two decades. In a scenario of global warming, it would be necessary to turn to them increasingly in order to stabilize GHG accumulations at some 'safe' level.