ON ENVIRONMENTAL ACCOUNTING FOR SUSTAINABLE DEVELOPMENT

M N Murty*

Abstract:

This paper while examining some practical problems of natural resource accounting highlights the importance of decentralized method of accounting. The accounting principles for estimating green GDP are found to be different for the exhaustible resources from those for renewable environmental resources in the standard models of sustainable development. The physical and monetary accounts of environmental resources especially those of air and water can be region or project specific and the national accounts cannot be obtained by simply adding up the environmental changes at the regional level. Development of environmental accounts at the regional level or project level provides micro foundations for integrated environmental and economic accounting. Detailed case studies discussed provide empirical insights into the suggested methods of accounting.

Key words: Natural resource accounting, sustainable development, shadow prices, pollution abatement cost, green GDP.

---

*This paper is prepared for the ongoing European Commission funded research project `A New Environmental Accounting Frame Work Using Externality Data and Input-Output Tools for Policy Analysis (EXIOPOL)'. It is mainly drawn from the recent research projects done at the Institute of Economic Growth, Delhi-110007, India. I am grateful to my colleagues Professors S.C. Gulati and B N Goldar who are also resource persons and a number of young researchers who worked with us for these projects. An earlier version of this paper was presented in the Indian Council of Social Science Research sponsored National Conference organized at the Institute of Economic Growth in March 2007.

I Introduction

Measurement of Net National Product (NNP) taking in to account the externalities of using natural resources requires the generalization of conventional national income accounts to be done for the economy. Conceptually these generalizations could be done as in the UN methodology of integrated environmental and economic accounting (UN, 1993) and in other recent attempts that use input-output models. However, there is a large gap between what is empirically achieved so far and the requirement of these generalized methods of accounting. These methods require an aggregation of changes in natural resource stocks at the micro level or an aggregation of changes over the firms and households to arrive at changes at the level of sectors and from the sector to the macro or national level aggregates. There are formidable empirical problems in measuring the changes in resource stocks introduced by firms or projects and the monetary valuation of these changes.

The UN methodology describes the generalization of production and use accounts for different sectors in the economy without explaining how the aggregation of changes in natural resources stocks introduced by firms and households could be done. The depletion of resource stock at the macro level could be unambiguously measured in the case of exhaustible natural resources while there are difficulties in measuring depletion in the case of environmental resource stocks. Production and use accounts at the sector or macro level could be prepared by simply adding the firm-level production and uses of fossil fuels or minerals or ores. The market determined resource rents could be used to prepare the monetary accounts of depletion of exhaustible resources. However in the case of environmental resource stocks, the depletion and the monetary valuation of it could be firm or region-specific. For example, in the case of atmospheric quality measured in Particulate Matter (PM10), the depletion should be with reference to an airshed and the in the case of water quality measured in Biological Oxygen Demand (BOD) it should be in the context of a watershed. The valuation of environmental quality measured either in terms of cost of improving it or in terms of benefits to the households could be also region or site- specific. Therefore for the environmental resource stocks, region or project specific, physical and monetary accounts have to be developed. While the national-level physical accounts of environmental changes could not be developed from the regional accounts the aggregate monetary accounts could be developed.

Detailed micro level studies of environmental resource accounting provide micro foundations of integrated environmental and economic accounting for measuring the Green GDP of countries. The objective of this paper is to examine some practical problems of natural resource accounting and highlight the importance of the decentralized method of accounting especially for environmental resource accounting. Case studies are minutely discussed for providing empirical insights into the suggested methods of accounting.

II. Environmentally Sustainable Income

Measurement of environmentally sustainable income requires a system of national accounts that integrates the environmental and economic problems. There are many definitions of sustainable income. The general view about sustainable income is that it is the maximum attainable income in one period with the guarantee that the same level of income will be available in future periods given the constraints on the resources, viz. labor, man made capital and natural capital. Therefore, income is directly related to the availability of man made and natural capital. Sustainable income defined in this way represents the welfare of the nation and there is a lot of discussion in the literature about whether the Net National Product (NNP) would appropriately represent it. Samuelson (1961) has argued, the rigorous search for a meaningful welfare concept leads to a rejection of current income concepts like NNP and arrives at something closer to a wealth like magnitude such as the present discounted value of future consumption. However, Weitzman (1976) has shown that in theory, the NNP is a proxy for the present discounted value of future consumption[1].

[1] See for details Murty and Surendar Kumar (2004).

It is long recognized that the conventional system of national accounts (SNA) to measure NNP has treated environmental resources and their role in the economy inconsistently. Under SNA, NNP increases when natural resource stocks are depleted and the quality of environment is reduced by pollution. As could be seen in Section 2 of this chapter, the correct approach to natural resources accounting is to account for the depletion of natural resources and the fall in the environmental quality in estimating the NNP. There is now a lot of literature about the problem of estimating NNP and the sustainable use of natural resources. Studies by Solow (1974) and Hartwick (1977, 1978a,b) have tried to derive the conditions under which real consumption expenditure might be maintained despite declining stocks of exhaustible resources (fossil fuels, minerals and metals). The main result of these studies known as the Hartwick rule, states that consumption may be held constant in the face of exhaustible resources only if the rents deriving from the inter-temporally efficient use of those resources are reinvested in the reproducible capital. The relationship of the Hartwick rule with sustainable income hinges on the assumption of the substitutability between manmade capital and natural capital. Solow (1974) has shown that in the case of manmade capital (which could be also natural capital) the optimal inter-temporal resource allocation requires the maintenance of existing capital stock by making the investment exactly equal to depreciation.

The main criticism about the Solow-Hartwick definition of sustainable income is that the manmade capital could not be substituted to natural capital. Natural capital can be exploited by man, but cannot be created by man. According to the thermodynamic school (Christensen, 1989), natural capital and manmade capital are not substitutable. One can think of two subsets of inputs, one containing the natural capital stock 'primary inputs' and another containing manmade capital and labor 'agents of transformation'. The substitution possibilities within each group can be high while they are limited between the groups. Increasing income means increasing the use of inputs from both groups. Given the limited substitutability between manmade capital and natural capital, it is necessary to maintain some amount of the natural capital stock constant in order to maintain the real income constant at the current level over time (Pearce et al., 1989; Klaasen and Opschoor, 1991; Pearce and Turner, 1990). This can be a heavy restriction on development if the current levels of natural capital stocks are chosen as a constraint, since it requires a banning of all projects and policies impacting the natural capital stock. As a way out of this problem, Pearce et al. suggest the use of shadow projects. These are the projects and policies designed to produce environmental benefits in terms of additions to natural capital to exactly offset the reduction in natural capital resulting from the developmental projects and policies. Daly (1990) has suggested some operational principles for maintaining natural capital at a sustainable level. For example, (i) in the case of renewable resources, set all harvest levels at less than or equal to the population growth rate for some predetermined population size, (ii) for pollution, establish assimilative capacities for receiving ecosystems and maintain waste discharges below these levels, and (iii) for non-renewable resources, receipts from non-renewable extraction should be divided into an income stream and an investment stream. The investment stream should be invested in renewable substitutes (biomass for oil).

In a free market situation, there may not be adequate incentives for the economic activities to undertake shadow projects and following the operative principles described above, for maintaining the natural capital at a sustainable level within the pace of economic development. The environmental regulation with the appropriate instruments and institutions could provide sufficient incentives for profit maximizing activities for the sustainable use of natural resources. A model of sustainable development described in the Appendix shows that there are prices associated with the natural resources that the firms and households have to pay for the unsustainable use of these resources. It also shows that the GDP estimated using the methods of conventional national income accounting does not account for the cost of sustainable use of environmental resources in the economy. Therefore, this cost has to be estimated and accounted for in the measurement of environmentally sustainable income or Green GDP. Also, the model shows that accounting principles for the cost of sustainable resource use are different for renewable and exhaustible natural resources.

Accounting Principles for Environmental Resources

Given that environmental resources are renewable, the change in the environmental resource stock, ΔS_t during a given time say a year is estimated as:

$$\Delta S_t = N(S_t) - E_t + A_t , \qquad (2.1)$$

where (S_t), the stock of environmental resource (quality of water resources or atmosphere) at time t; $N(S_t)$ the natural rate of regeneration of this stock (natural rate of assimilation of pollution loads); (E_t,), the rate of depletion of stock (rate of degradation of environmental quality); and (A_t), the rate of pollution abatement. The environmentally corrected Net National Product (ENNP) with the sustainable use of environmental resources could be estimated as:

$$ENNP = C_t + U_L L_t / p_t + \Delta K_t + M^{/} \Delta S_t , \qquad (2.2)$$

where (C_t), is the consumption,;(L_t), the labor employment; (ΔK_t), the value of change in manmade capital or investment, (ΔS_t), the change in environmental capital; (U_L), the marginal disutility of labor; (p_t), the price of consumption good; and $M(A_t)$ and ($M^{/}$) are respectively the pollution abatement cost function and the marginal cost of pollution abatement. The accounting principle therefore is to evaluate the changes in environmental resource stocks at the marginal costs of avoiding the depletion of the stocks. The marginal cost of avoiding the depletion is the price of an environmental resource in the context of sustainable development.

Accounting Principles for Exhaustible Natural Resources

Extraction of exhaustible natural resources like fossil fuels, minerals, metals and ores and their use in various economic activities has implications for sustainable development in two important ways: intergenerational equity and environmental degradation. Given the property right of an exhaustible resource to the present and future generations, sustainable development has to ensure just distribution of benefits from the resource to present and future generations. Exploitation of exhaustible resources contributes to environmental degradation. Mining of resources could result in deforestation, land degradation and water and air pollution which could be identified by attempting full life cycle analysis of resource use. Accounting principles require first establishment of the change in the stock of exhaustible resources during the accounting period and the monetary value of this stock from the inter-generational equity point of view. Also, it is required to find out the change in the environmental resource stocks consequent to the extraction of exhaustible resources in the accounting period and the monetary value of this change.

Changes in the resource stocks in this context have to be estimated as follows:

The rate of depletion of the resource stock ΔR, if fresh discoveries of the resource are not there, is given by:

$$\Delta R, = - Y_t , \tag{2.3}$$

where R_t and Y_t represent respectively, the stock of exhaustible resource, say coal and the amount of resource extracted. The rate of depletion of environmental resource stock ΔS_t consequent on the extraction of exhaustible resource is given by:

$$\Delta S_t = N(S_t) - \alpha Y_t + A_t , \tag{2.4}$$

where A_t is the rate of pollution abatement and α is the rate of environmental resource degradation per unit extraction of Y_t. The environmentally corrected Net National Product (ENNP) with the sustainable use of exhaustible resources could be estimated as,

$$ENNP = C_t + U_L L_t / p_t + K_t + M^{/} S + \{((F_y - v_t) - \alpha M^{/})\} R_t . \tag{2.5}$$

The first four components are the same as those in equation (2.2). The term $\{((F_y - v_t) - \alpha M^{/})\}$ in the equation could be interpreted as the generalized Hotelling rent on an exhaustible resource after accounting for the cost of avoiding environmental degradation arising out of use of the resource. By using say one tonne of fossil fuel, α tons of pollution is generated and the cost of abatement of it is $\alpha M^{/}$ which has to be accounted in defining the Hotelling rent. It is so because the cost of depletion of environmental quality due to pollution evaluated at the shadow price, the marginal cost of pollution abatement, is already accounted in measuring ENNP through the fourth component in equation (2.5).

III. Integrated Economic and Environmental Accounting

Measurement of environmental costs and benefits of sustainable development requires measurement of the effects of development activities on the natural resource stocks in the economy. As discussed in the above Section and in Appendix A, measurement of National Income with sustainable development requires the identification of aggregate changes in the natural resource stocks and the monetary valuation of these during the given accounting period. The UN methodology[2] of integrated environmental and economic accounting recognizes this and suggests the development of physical and monetary accounts of natural resource stocks as a satellite system to a core system of conventional national income accounts. There are two important steps in the development of integrated economic and environmental accounting: First namely the description of stocks of natural assets in physical terms and the measurement of changes in stocks during the accounting period; and the second is the valuation of natural assets. Natural assets provide both marketable and non-marketable services and therefore their valuation requires the use of market and non-market valuation techniques.

The development of integrated environmental and economic accounts starts with the description of two proto types of environmental accounting in physical terms: material energy balances and natural resource accounting. Material and energy balance accounting shows raw materials as inputs, transformation process in the economy, and flows of residuals resulting from the economic uses of materials back to the environment. Transformation processes within the natural environment are excluded. Natural resource accounting describes the stocks and stock changes of natural assets, comprising biological assets (produced or wild), subsoil assets (proved reserves), water, air and land areas with their terrestrial and aquatic ecosystems. Biological natural assets consist of plants and animals of economic importance. Land areas include area as well as related

[2] UN (1993b)

biological ecosystems. Subsoil assets consist only of proved reserves. Water and air are accounted in so far as they are used or are affected by the economic activities.

The methods of valuation of environmental services could be classified as three different valuation types: (a) market valuation according to the concept of the non-financial asset accounts in the conventional system of national accounts, (b) maintenance valuation, which estimates the cost necessary to sustain at least the present level of natural assets, and (c) Nonmarket valuation using hypothetical behavioral methods: contingent valuation methods and the observed behavioral methods such as hedonic prices, travel cost and household production functions for estimating the value of consumptive services of the natural environment.

The maintenance valuation method uses actual or hypothetical cost data. Expenditures required for maintaining the services of natural environment constitute the actual cost. These are the costs for an increase in environmental protection activities that prevent the degradation of natural assets. These could be interpreted as the value that the producer or polluter places on the environmental services he receives. The hypothetical cost of using environment is the cost that would have been incurred if the environment had been used in such a way that would not affect its future use. The rationale behind using this method of valuation is the concept of sustainable income discussed in the earlier sections.

Estimation of values that the households place on environmental services requires the use of non-market valuation methods. There is a lot of literature now about the use of these methods for estimating the household values of environmental resources (Freeman, 1993; Mitchell and Carson, 1989; Murty and Surender Kumar (2004)). The hypothetical behavioral methods comprising contingent valuation and other variants of this can be used to measure both user and non-user benefits from environmental resources. The observed behavioral methods indirectly use market information to estimate user benefits.

The shadow price of an environmental resource is defined as the value of unit depletion of the resource measured in terms of foregone net national product as shown in Section 2. Dasgupta and Maler (1998) have shown that the same definition of shadow price of a natural resource could be carried to the second best situations in the economy, especially for valuing small perturbations in natural resource stocks caused by an investment project. There are two views about the shadow prices according to the two approaches of valuation described above. According to one view as already mentioned earlier, the shadow price of an environmental resource could be defined as the cost to the producer to avoid a unit depletion of an environmental resource. Therefore in this case, the shadow price could be defined as the marginal cost of air or water pollution abatement. This definition of shadow price is based on the idea of cost of environmentally sustainable development. Another view is that it represents the environmental values of households: user and non-user values and option values which are the consumptive benefits from a unit of resource, say an acre of forest land, a unit improvement in atmospheric or river water quality. Since the environment is a public good, as for example, the atmospheric quality in an urban area, the shadow price of air quality is the sum of consumptive benefits to all residents of that area from one unit improvement in the air quality. In the first best situation in the economy, the two methods of measuring the shadow price of an environmental resource will provide the same estimate because in this case the marginal willingness to pay for the environmental service has to be equal to the marginal cost of avoiding the environmental degradation. In a realistic situation in the economy, which is normally the second best, estimates based on the two methods could differ. One could as well arrive at a result in which the marginal willingness to pay is higher than the marginal cost of avoiding degradation.

IV. Measuring Changes in Environmental Resource Stocks

Incorporation of the environmental effects of developing activities in the measurement of Green GDP requires an identification of the effects of these activities on the environmental resource stocks. An aggregate change in the stock of a natural resource during the accounting period has to be estimated taking into account the depletion of the resource at the project or activity level. Aggregation has to be attempted at the sectoral and macro level as required by the UN methodology of integrated environmental and resource accounting. Sectoral and macro level aggregation of depletion and the monetary valuation could be unambiguously attempted in the case of exhaustible resources. For example the depletion of fossil fuels could be measured as defined by Equation (2.3) and the monetary value of this could be estimated using the imputed rents. However, in the case of renewable resources, depletion could not be unambiguously quantified at the sectoral or macro level and estimation of the monetary value of depletion fraught with more problems.

Take for example an investment project. The project may be contributing to the depletion of environmental resources by generating air and water pollution loads and causing deforestation, as it is the case with a thermal power plant or with a paper and pulp mill. The depletion could not be simply measured as an annual flow of pollution (in tonnes) generated and forest degraded (in acres) by the project. The depletion of a renewable natural resource has to be measured as explained by the Equation (2.1). The depletion of air or water quality in this case is the annual flow of pollution from the project net of carrying capacity of environmental media. The carrying capacity could be defined only to a micro water or air shed in the country and it is clearly site specific. If the project is located on a big water body with carrying capacity of water pollution higher than the pollution load generated, the depletion of water quality by the project becomes zero. The depletion of environmental quality by a project is therefore site specific. A project located in a more densely industrialized area will have high environmental depletion in comparison to a similar project located in a less densely industrialized area. It is because the industries have to share the limited carrying capacity of the local environmental media. The physical accounts of changes in the environmental quality could be made for a local air shed or water shed and the monetary accounts could be developed by valuing these changes at the marginal cost pollution abatement by the polluter. Allowing emission trading between the polluters within the water shed as explained in Appendix B could result in the equalization of marginal cost of pollution abatement across the polluters which is the price of emissions specific to the water shed. Given that the emission trading may not be meaningful across the water sheds, there could not be one emission price or the marginal cost of water pollution abatement for the national economy. Therefore to start with, region specific physical and monetary accounts of local pollutants like PM_{10} and BOD have to be prepared and then an aggregation of monetary accounts of different regions could be done for preparing the national accounts.

Accounting for global externalities in the measurement of Green GDP poses different types of problems in measuring changes in resource stocks and in the valuation of these. Additions to the stock of green house gases in the atmosphere due to anthropogenic activities in the world economy during an accounting period depends on the carrying capacity of global commons, the oceans, forests and atmosphere itself. For example, there will be an addition to the stock of CO_2 in the atmosphere if the global emissions exceed the carrying capacity of global commons. Therefore, CO_2 emissions in the national economy may not all be contributing to the addition of the global carbon stock depending upon the emissions in the rest of the world economy. Even if all the countries agree to maintain the current level of the CO_2 stock in the atmosphere, there could be problems in sharing the reduction of emissions over and above the carrying capacity of the global commons. If there is an agreement to this effect among the countries, the physical accounts of emissions reductions required in a country could be made. Monetary accounts of carbon emission reductions could be made valuing the reductions at the marginal cost pollution abatement in the country concerned. There could be only one price or the marginal cost of abatement of CO_2 emissions for the national economy because emission trading between the polluters in the country could be possible in this case.

The annual flows of pollution at the project level are given in terms of tonnes of PM_{10} for air pollution and tonnes of BOD for water pollution. For finding out the value that urban residents place on a tonne of emissions of particulate matter or the value river users place on a tonne of emissions of biological oxygen demand by the project, one has to study the relation between the pollution at source and the ambient environmental quality. These relationships could be found by modeling urban air quality or river quality. For example, by modeling urban air quality, one could find the effect of one tonne reduction of particulate matter by an investment project on the ambient air quality measured in micrograms of particulate matter in a cubic space (μ gms/m^3). Appendix B describes a method of air quality modeling. Suppose it results in 1000^{th} of a microgram reduction in ambient air pollution, one could find the value placed on this reduction by a representative individual using the estimated marginal willingness to pay function for air quality improvement. The extrapolation of this value for all the urban residents could provide an estimate of the shadow price of a tonne of particulate matter. This shadow price is also site specific. The value placed by households on one tonne reduction of pollution by a project located in a densely populated area will be higher than the value placed in a less densely populated area. Therefore, a project located in a more densely industrialized and populated area contributes to more pollution and greater damage than others.

The case studies presented in the following sections highlight some empirical problems in preparing environmental accounts at the sector, region and project levels. They show how micro-level accounts have to be integrated to develop national environmental and economic accounts. These case studies deal with the two most important air polluting sectors: transport and thermal power generation and the air pollution in an urban region.

V. Enironmental Accounting for Thermal Power Sector

5.1. Introduction

Natural environment provides waste disposal services as productive inputs to industry. Given the environmental regulation, producers place a value on these inputs similar to the way they value other conventional inputs such as labor, man made capital and materials. Environmental regulation meant for ensuring an environmentally sustainable industrial development imposes a cost on the industry. The UN methodology for an integrated environmental and economic accounting calls this cost as maintenance cost or the cost to the industry for maintaining the quality of environment at its natural regenerative level. A model in the theory of production is used in this study for estimating the maintenance cost. The model describes the technology of power generation as one of producing jointly good output, power and bad output, pollution load, using the output distance function. The producer demand prices for waste disposal services from the environmental media could be defined as the opportunity costs in terms of good output foregone to reduce bad output in this model. In any attempt to measure Green GDP, estimates of these prices are needed to value changes in environmental quality caused by the developmental activities. A case study of thermal power generation in Andhra Pradesh in India is done for preparing the physical monetary accounts of environmental pollution at the sectoral level.

5.2. Thermal Power Generation in Andhra Pradesh

Andhra Pradesh Power Generation Corporation (APGENCO) (formerly known as Andhra Pradesh State Electricity Board, APSEB) came into existence on February 1, 1999. APGENCO was supposed to acquire the power plants established by APSEB and establish, construct and operate power-generating stations. All the five plants under study are now owned by APGENCO and are subjected to environmental regulations in the generation of power. The corporation has an unwritten environmental policy to comply with the relevant environmental legislations and regulatory requirements for the establishment and operation of the power stations. High efficiency Electro-static Precipitators (ESPs) are installed to control Suspended Particulate Matter (SPM) in the flue gas. All new plants are designed for the SPM level of 100 mg/NM^3 a limit set by the Andhra Pradesh Pollution Control Board (APPCB). Old units are upgraded or are under upgradation for 50/115 mg/NM^3 against a limit of 115 mg/NM^3. The latest micro processor based EPIC-II controllers are installed for improvement of collection efficiency and a reduction of power consumption. Online flue gas dust monitoring systems are installed in some plants.

In India, the electricity sector is regulated and the state regulatory commissions determine the price of electricity for different categories of consumers accordingly and Andhra Pradesh is no exception. Cross subsidies are widespread and domestic and agricultural consumers are charged lower prices in comparison to production costs, but commercial and industrial consumers have to pay higher prices.

The output distance function is estimated using data for five coal fired thermal power generating plants belonging to APGENCO. The data set used constitutes a panel consisting of monthly observations on variables during the years 1996-97 to 2003-04. It contains 480 observations on electricity produced, air pollutants SPM, SO_2 and NO_x

generated as well as coal and other inputs used by the five electricity-generating plants. Electricity generated is considered as a good output while the three pollutants SPM, SO_2 and NO_x generated are taken as bad outputs in the estimation. Table 5.1 provides the descriptive statistic of the variables used in the estimation of the distance function.

For the estimation of shadow prices of bad outputs we need the information on electricity prices. Here we are assuming that the price paid by industrial consumers is equal to the price prevalent in a free market as it is safe to assume that industrial consumers are rational decision makers who have to take decisions for the profit motive. In 2003-04, the industrial consumers were paying Rs. 3.6 per unit of electricity.
The variables used in the study are as below:
SPM, SO2, and NOx: Monthly loads in tonnes discharged by the power plant were computed by multiplying the monthly average concentration of the pollutant (mg/NM^3) with the monthly volume of stack discharge (NM^3) for each plant.

Electricity: Electricity produced by the plant during a year in (million units).

Capital: Capital stock of a plant observed at the beginning of a year which is assumed to be fixed for the rest of the year.

Coal: Annual consumption of coal by the plant (in tonnes).

Wage Bill: Annual wage bill of a plant (in million rupees).

Table 5.1: Descriptive Statistics of the Variables Used in Study

Variable	Unit	Mean	Standard Dev.	Maximum	Minimum
Electricity	Million Units	298.28	13.91	933.58	0.01
SPM	Tonnes	653	0.033	3.526	0.018
SO_2	Tonnes	874	0.049	4.268	0.004
NO_x	Tonnes	139	0.013	1.984	0.001
Coal	Tonnes	223460	9.93	667.05	0.01
Capital	Rupees millions	1913.231	905.46	62395.28	148.59
Wage Bill	Rupees millions	255.628	111.03	9332.04	344.16

5.3. Shadow Prices of Pollutants and Pollution Taxes

Using the estimated output distance function, the shadow price of a pollutant is estimated in terms of units of good output foregone for one unit reduction in pollution. The current electricity tariff for industries in AP is on the average Rs. 3.60 per unit. Using this price, shadow prices of pollutants could be expressed in rupees for a representative plant of APGENCO as Rs. 1043, 5867 and 11539 respectively per tonne reduction of SPM, NO_x, and SO_2 as reported in Table 5.2.

Table 5.2: Shadow Prices of Pollutants

(Rs, per tonne)

Industrial Pollutants	Mean	Standard Deviation
SPM	1043	1067
SO_2	5867	8706
NO_2	11539	21153

Estimation of pollution taxes using the Taxes-Standards method requires estimates of the marginal cost of pollution abatement and the data on pollution standards. The shadow price reported in Table 5.2 could also be interpreted as the marginal costs of pollution abatement. Using the estimated output distance function for thermal power generation in AP, plant-specific shadow prices could be calculated. The marginal cost of pollution abatement for each pollutant could be obtained by finding a relationship between the shadow price of the pollutant and pollution load. The marginal cost of pollution abatement of a plant could depend on output, pollution load and plane specific characteristics among others. Specifying this relationship as stochastic, the marginal cost of the pollution abatement function for APGENCO is estimated each for SPM, SO_2 and NO_x as given in Equations 5.1, 5.2 and 5.3, respectively. In these equations, the dependent variables are shadow prices of pollutants (SPMS, SO_2S, NO_xS) and independent variables are electricity output, pollution concentrations (SPMC, SO_2C, NO_xC), plant specific dummy variables (D_i, i = 1…4), and time. There is a rising marginal cost with respect to pollution reduction as expected.

SPM

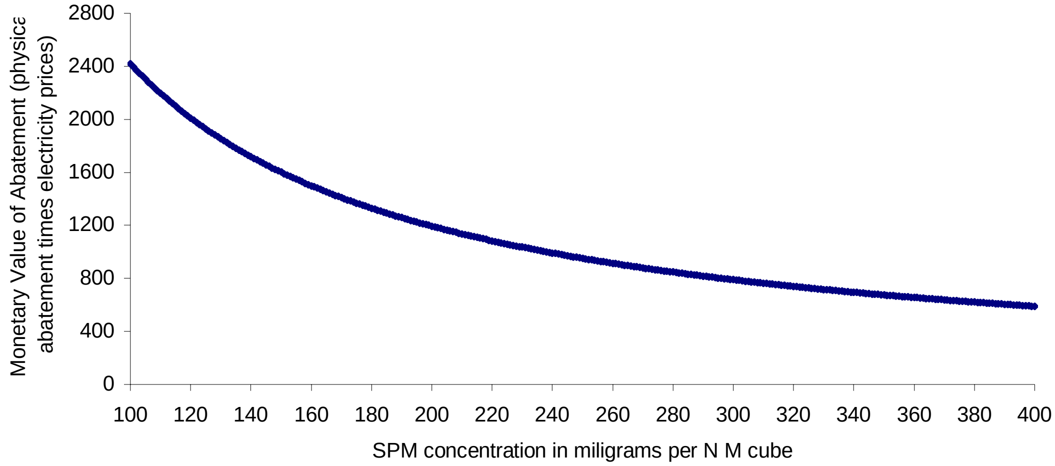
$$\ln SPMP = 11.82 + 0.255^* \ln (OUT) - 1.02^* \ln (SPMC) + 0.705^*D1 + 0.308^*D2 - 0.57^*D3$$
(22.80) (2.92) (-13.71) (2.96) (1.00) (-3.31)

$$0.108^*D4 - 0.22^*TIME$$
(0.55) (13.71) (5.1)

Adjusted R^2 = 0.7822

The following figures depict the marginal pollution abatement cost function for SPM, SO_2 and NOx. On the y-axis the marginal cost of abatement and on the x-axis concentrations of SPM, SO_2 and NOx are measured.

Figuare 5.1: Abatement Function for SPM concentration



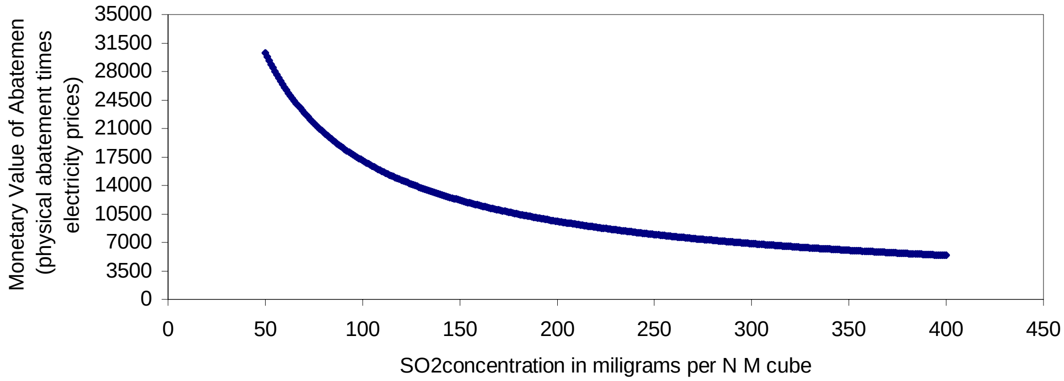
SO_2

$$\ln SO_2P = 9.33 + 1.012^* \ln (OUT) - 0.835^* \ln (SO_2C) -02.16^*D1 -2.27^*D2 - 1.69^*D3$$
(27.24) (11.73) (-14.85) (-8.37) (-6.68) (-10.13)

$$-0.352^*D4 - 0.073^*TIME$$
(-1.47) (-3.01) (5.2)

Adjusted R^2 = 0.8196

Figure 5.2: Abatement Function for SO2 concentration

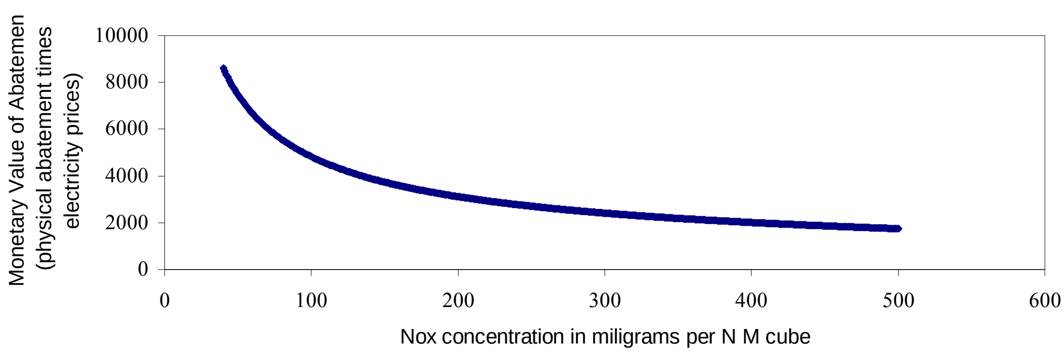


NO_X

$\ln NO_XP = 4.94 + 1.21^* \ln(OUT) - 0.63^* \ln(NO_XC) - 3.88^*D1 - 2.41^*D2 - 0.93^*D3$
(14.67) (13.48) (-10.67) (-16.58) (-7.50) (-5.23)
$-1.38^*D4 - 0.27^*TIME$
(-6.34) (10.8) (5.3)

Adjusted $R^2 = 0.8062$

Figure 5.3 : Abatement Function for NOx concentration



Using the above abatement cost of functions and using the MINAS Stack Emission Standards of 115, 80 and, 80 milligrams per Nm^3, respectively for SPM, SO_2 and NO_x, ,the tax rates are computed as Rs. 2099, 20519, and 5554.

5.4. Cost of Environmentally Sustainable Thermal Power Generation and Measurement of Green GDP

Physical and monetary accounts of air pollution for the thermal power generating sector have to be prepared for estimating the cost of environmentally sustainable power development or the maintenance cost, the cost of maintaining the environmental quality at its natural regenerative level. Scientifically, the environmental standards (Minimum National Standards, MINAS in India or WHO standards) are supposed to be designed taking into account the natural regenerative capacity of the environment media. Therefore, one way of measuring the depletion of air quality from power generation is to consider the difference between the actual pollution load and the pollution load corresponding to the standards. This method of measuring depletion is consistent with the definition of depletion of environmental quality in equation 2.1. Row 2 of Table 5.3 provides estimates of depletion of air quality by a typical plant of APGENCO. Given the shadow prices of air pollutants reported again in row 3 of the same table, the estimates of cost of avoiding this depletion or the cost of complying with the pollution standards for an average plant are estimated as reported in row 4. The annual cost of reducing the pollution levels of SPM, SO_2, and NO_x from the current levels to zero in all plants of APGENCO is estimated as Rs. 534 million. This cost has to be accounted in the measurement of Green GDP or environmentally corrected net national product (ENNP).

Table 5.3: Physical and Monetary Accounts of Air Pollution For APGENCO

	SPM	SO_2	NO_X
Load (Tonnes/yr.)	7836	10488	1668
Shadow Price (Rs.)	1043	5867	11539
Cost of Abatement (Rs. million)	8.173	61.533	19.247

Note: Row 2 of Table shows the data of observed emissions of SPM, NO_X, and SO_2

VI. Environmental Accounting for Urban Airsheds

Households place a value on the ambient air quality in urban areas. The physical accounts of air pollution for an urban area describe the ambient air quality during an accounting period. There are MINAS standards in India and WHO standards for ambient urban air quality which are supposed to be fixed by taking into account the carrying capacity of urban air sheds. The physical accounts describe the excess of ambient air pollution over these standards. Estimates of household values of urban air quality could be used to estimate the damages households receive from the air pollution in excess of safe standards. Some recent studies in India (Murty, Gulati and Banerjee, 2003; Murty and Gulati, 2005) provide estimates of household marginal willingness to pay function for urban air quality improvement in the cities of Delhi, Kolkata and Hyderabad using the hedonic property values method of environmental valuation. Table 6.1 provides an estimate of the household marginal willingness to pay function for reduction in Total Suspended Particulate Matter (TSPM) in Delhi while Fig. 6.1 provides the graph of this function.

The consumer surplus generated by the reduction of SPM concentration from the current average to the safe level of 200 μ gm/m^3 is computed by integrating the estimate of inverse demand function given in Table 6.1 within 200 μ gm/m^3 as the lower limit[3] and the current average level of pollution in the respective cities as the upper limit. The estimated consumer surplus also measures the average willingness to pay by a representative household for reduction in the ambient air pollution from the current average to the safe WHO or MINAS[4] standards. The annual welfare gains to a typical household from reducing SPM concentration from the current level to the MINAS standard of 200 μ gms/m^3 in Delhi are Rs.23,354. According to the 2000 census, Delhi has an urban population of 12.8 millions with the sample average household size being 5.46. Thus, there are 23,47,942 estimated urban households in Delhi. The annual benefits from reducing the SPM concentration to safe level in Delhi are estimated as Rs. 54,833 million. A similar estimate for the urban area of Kolkata is Rs. Rs.37,026 million.

---

[3] 200 μ gm/m^3 is the safe WHO and MINAS standard for residential area in India.
[4] MINAS: Minimum National Standards for Environmental Pollution in India.

Having these estimates for all the urban areas in India, an estimate of damages from the current levels of urban air pollution could be obtained. The NNP of India corrected for the urban air pollution could be obtained after accounting for these damages in its estimation.

Alternatively, the abatement cost method could be used for the valuation of urban pollution. There could source-specific air pollution standards as described in the earlier section on thermal power generation and the cost of complying with these standards by the polluters could be estimated. Ideally, the source specific air pollution standards and ambient standards have to be linked in the sense that if the sources comply with the standards, the ambient air quality standards are met. Source-specific physical accounts could show the excess pollution loads at source over the loads corresponding to the standards. The cost of abatement of this excess pollution has to be accounted in the estimation of NNP corrected for urban air pollution.

These two valuation methods provide estimates of cost and benefits of air pollution abatement. However, the cost estimates are for the air pollution at source and the benefits estimates are for the ambient air pollution. Urban air quality modeling establishes the link between the pollution at source and the ambient pollution so that one could compare the cost of air quality improvement to the benefits. A recent study by Sudhakar Yedla et al. (2002) has done urban air quality modeling for the cities of Delhi and Mumbai for finding the relationship between the emissions from different sources and the ambient air quality in the city. This study makes an estimate of reduction of TSPM by 2.37 thousand tonnes from the transport sector in Delhi in comparison to the business-as-usual scenario in the year 2005 due to introduction of CNG in all buses and small cars. This intervention results in a 30 per cent reduction in the contribution of the transport sector to the ambient air pollution, measured as TSPM concentration in a cubic meter. An average of the estimates of contribution of the transport sector to the hourly ambient concentration of SPM at seven monitoring stations in Delhi in the business-as usual-scenario works out to be $0.75\mu / m^3$. A 30 per cent reduction in this amounts to $0.215\mu / m^3$. Therefore, an estimated reduction in the ambient pollution of TSP in Delhi due to one tonne reduction of TSP at sources works out to be mg $0.00009\mu / m^3$. Estimates described earlier show that a typical household in Delhi is willing to pay Rs. 152 annually for one micro gram reduction of atmospheric concentration of TSPM. Now the household annual willingness to pay for this reduction becomes Rs 0.014 and extrapolating it to the estimated 23,47942 urban households in Delhi, the shadow price of a tonne of TSPM becomes Rs. 32,871.

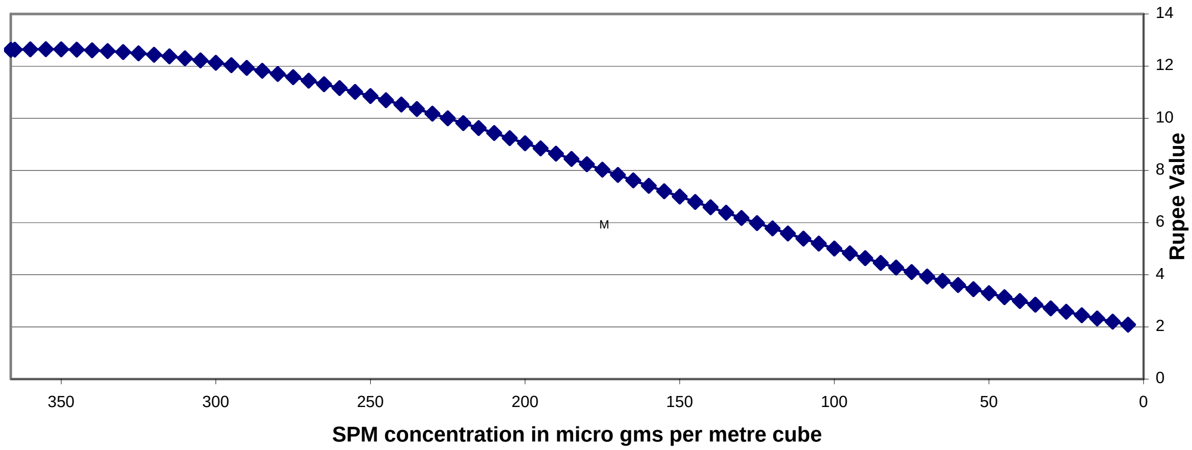
Urban air pollution is an environmental externality created by polluters and therefore the shadow price of air pollution defined above depends upon the size of the exposed population to pollution. For example, a typical urban settlement in India has a population of one million with 2.5 lakh households. It is important to see what is the shadow price of a tonne of TSPM if 2.5 lakh households are exposed to air pollution levels currently found in the mega cities of Delhi, Mumbai, Kolkata, Hyderabad. etc. The studies mentioned above (Murty, Gulati and Banerjee, 2003; Murty and Gulati, 2005) also provide estimates of the household marginal annual willingness to pay for the reduction of one microgram concentration of TSPM in the cities of Kolkata and Hyderabad as Rs. 96.76 and Rs. 220.67 respectively. Given these estimates, the average of household marginal willingness to pay for the reduction of TSPM for the three cities could be computed as Rs. 156.33. The shadow price of one tonne of TSPM in an urban area having one million population in India is estimated as Rs. 3525.

Table 6.1: Estimates of Marginal Willingness-to-pay Equation for Delhi

Log Values of Variables (Expected Sign)	Box Cox Transformation $\theta = 0.0736085$**
	Coefficients (Chi^2 statistics)
Constant	-0.5406424
Education X_{18} (+)	0.0316471*** (53.814)
Income X_{19} (+)	2.6e-06*** (294.164)
SPM X_{13} (+)	0.0117879*** (71.954)
Sq SPM X_{20} (-)	-0.0000166*** (90.493)
Perception about Air Quality X_{10} (+)	0.1780826*** (43.498)
	Sigma = 0.5686012
Uncentred R^2 = 0.555	LR chi ^{2} (5) = 658.27 Probability > Chi^2 = 0.000
	Log Likelihood = -3707.6189
Test H_0	Chi ^{2} Statistics
$\theta = -1$	1284.85***
$\theta = 0$	5.28**
$\theta = 1$	725.40***

Source: Murty, Gulati and Banerjee (2003).
Note: *(**) & (***) denotes significance at 10 (5) & (1) % levels.

Figure 6.1: Inverse demand function for clean air in Delhi



Source: Murty, Gulati and Banerjee (2003).
Note: The graph is generated from the Current average level of SPM of 366.31 μ gm/m^3 to zero SPM, while safe limit for SPM concentration is 200 μ gm/m^3.

VII. Environmental Accounting for Road Transport Sector

Road transport contributes to the maximum amount of air pollution in urban areas. It accounts for two thirds of air pollution in Delhi, the capital city of India. Pollution from the transport sector could be reduced through inter fuel and inter modal substitution. Substitution of compressed natural gas (CNG) to petrol and diesel and switching the mode of transport from road to metro rail could significantly reduce air pollution in Delhi. Physical accounts of air pollution for road transport could be prepared given the emission coefficients and the number of vehicles on road for different types of vehicles. For example, given the estimates of emission coefficients with and without CNG introduction for different vehicles, estimates of emission reduction with CNG could be obtained. Monetary accounts of emission reduction could be obtained given the estimates of annual cost per vehicles for using CNG. The incremental annual cost of using CNG by all the vehicles in the transport sector could be taken as an estimate of the air pollution abatement cost of the road transport sector. In a situation in which no CNG is used in the road transport in the economy, the hypothetical cost of introducing CNG has to be deducted from the NNP for arriving at an estimate of NNP corrected for air pollution from the road transport. A recent study by S. Chatterjee et al. (2006) provides estimates of physical and monetary accounts of air pollution of the road transport for Andhra Pradesh state.

Table 7.1: Pollution Loads by Vehicular Traffic in Andhra Pradesh

		CO2	*HC*	*NOX*	*PM*
Pollution Load (Tonnes /Year)	**Pre Euro**	369463.9	148887.7	45556.2	9285.2
	Euro II / Bharat II	147389.8	70309.7	30402.7	3157.9
Load Reduced/ Physical Accounts (Tonnes /Year)	*Pre Euro to Euro II*	222074.1	78578	15153.6	6127.3

Table 7.2: Total Annualized Cost of Conversion of Technology of Different Vehicles Operating in Andhra Pradesh

Vehicle Category	CONVERSION	Annualized Cost/Vehicle (Rs.)	No. Of Vehicles on road 2001-02	Total Annualized Cost 2001-02 (Rs.)
Passenger car	Pre Euro to Euro III	5312.5	370398	1967739375
Trucks	Pre Euro to Euro III	17212.5	160185	2757184313
Buses	Pre Euro to Euro III	17212.5	215769	3713923913
Two Wheelers	Pre Euro to Euro III	4621.87	3609373	16682052788
Three Wheelers	Pre Euro to Euro III	5843.75	171834	1004154938

Table 7.3: Annualized Cost of Vehicles for Using Fuels Compatible With Euro Norms in A.P.

Vehicle Category	Pre Euro to Euro II		Pre Euro to Euro III	
	Per Vehicle Cost	Total Cost	Per Vehicle Cost	Total Cost
PC	1338	495505110	1877	695208525
Bus	6477	1397615216	9014	1945014480
Truck	7202	1153651249	10023	1605497412
Two Wheeler	581	2097546333	815	2942921044

Changing the mode of transport from road to metro rail in an urban area could be the cost effective alternative for reducing air pollution. For example, Metro rail is gradually substituting road transport for passengers in Delhi. Fewer vehicles and the decongestion for the residual traffic on Delhi roads due to Metro could lead to reduced air pollution. A recent study by Murty et al. (2006) has estimated the cost savings in reducing air pollution in Delhi due to the metro. The distance saved by a vehicle due to decongestion is estimated by multiplying the time saved with the speed of a vehicle in a decongested situation. An estimate of the pollution reduction by a vehicle in this context could be obtained by multiplying the distance saved by the relevant emission coefficient for different pollutants for each category of vehicle. The emission coefficients for different vehicles as per the Euro II norms are given in Table 7.4. Estimates of reduction in distance traveled every day due to the decongestion effect are obtained for cars, two-wheelers and buses as 9.18 kms, 7.65 kms and 69.72 kms, respectively. Table 7.5 reports the estimates of air pollution loads prevalent following the to decongestion avoided due to Metro. The monetary value of these pollution loads are estimated using the estimates of shadow prices of pollutants made in some recent studies in India (Murty, Surender Kumar and Dhavala, 2006) which are reported in the same table.

Table 7.4: Emission Factors of Vehicles as per Euro II Norms (kg/km)

	PM	NO_X	HC	CO
Bus	0.05	0.87	2.75	0.66
Car	0.03	0.2	0.25	1.98
2- wheeler	0.075	0.3	0.7	2.2
3-wheeler	0.08	0.02	1.45	0.29

Source: Chatterjee, Dhavala and Murty (2006).

Table 7.5: Reduction in Pollution Load due to decongestion and its Monetary Value for the Year 2011-12 with the Assumption that All Vehicles Use EURO II Technology without Metro

Reduction in Pollution Load	HC	PM	NO_X	CO_2
Due to decongestion	643	77	514	8008
Shadow Prices (Rs)	502	4777	6724	448
Value (Rs. Million)	32	0.37	4	4

Source: Estimated as explained in the text.

The vehicular technology complying with Euro III norms or using CNG as a fuel could have similar effects on the air pollution in Delhi. Table 7.6 provides the estimates of diverted traffic due to Metro. A major component of the monetary value of reduction in air pollution due to the Metro could be obtained as the savings in the cost of pollution abatement due to the diverted traffic. A recent study (Chatterjee, Dhavala and Murty, 2006) provides estimates of the annual cost of Euro III technology for different vehicles. Table 7.6 provides monetary accounts of air pollution reductions due to the metro in Delhi.

Table 7.6: Estimates of Monetary Value of Pollution Reduction in the year 2011-12 due to the Metro

Different Mode of Vehicles	Diverted Traffic	Annualized Cost of Conversion of Technology per vehicle (Rs.)	Annualized Incremental Production Cost of Fuel per vehicle (Rs.)	Monetary Value of Reduction in Pollution Due to fewer vehicle (Rs. million)	Monetary Value of Reduction in Pollution Due to Decongestion (Rs. million)	Monetary Value of Total Reduction in Pollution (Rs. million)
Bus	9450	17212	14790	302	11	314
Car	164252	5312	1876	1181	10	1191
Two-wheeler	985789	4622	816	5360	18	5379
Total	1159491	27147	17482	6843	40	6883

Source: Estimated as explained in the text.

Estimates of savings in air pollution abatement cost due to the metro in Delhi will form part of the annual benefits of the metro as an investment project. In the ex post scenario with metro, these benefits are already accounted for in the estimation of NNP of India using the conventional national income accounting methods. In the ex ante scenario without metro and CNG and if the metro is a lower cost option in comparison to the CNG in Delhi for reducing pollution, that part of the cost of the metro attributable to an air pollution reduction has to deducted from the conventional measure of NNP[5].

[5] Air pollution reduction is one of the benefits of Metro the main benefits being serving the passenger traffic in Delhi. Also it is difficult to estimate unambiguously the share of air pollution reduction in the total cost of Metro.

VIII. Conclusion

The model of sustainable development described in this paper shows that the accounting principles for measuring the Green GDP of a nation for environmental resources are different from those used for exhaustible resources. In the case of environmental resources, the cost of a sustainable use of the resource has to be accounted. For exhaustible resources, the rents for the resource extraction and the cost of avoiding the environmental degradation consequent upon the resource extraction have to be accounted.

It is possible to develop the sector or macro level physical accounts of exhaustible resources by adding the firm-level changes in resource stocks and to use the market prices to develop corresponding monetary accounts. However, the environmental resource depletion and the monetary valuation of this could be site or project-specific. Development of national level physical accounts of environmental changes is not possible using the site-specific and regional accounts while it is possible to prepare corresponding monetary accounts.

The case studies of valuation and environmental resource accounting attempted here provide insights into the micro foundations of integrated environmental and economic accounting for estimating the Green GDP. Two studies of the most important air polluting sectors: thermal power generation and road transport in the Andhra Pradesh state of India describe possible approaches for measuring the cost of environmentally sustainable development or maintenance cost as described by the UN methodology. Also, a case study of an important transport project in India, Delhi Metro provides insights into the development of physical and monetary accounts of air pollution at the project level.

The case study of the urban air shed of Delhi describes the approaches of developing natural resource accounts for urban air pollution. It shows that the environmental damages are site specific. The population density and the actual pollution load in the air shed determine the benefits from the reduction of a tonne of particulate matter.

Appendix A

A.1. Shadow Prices of Environmental Resources and Net National Product

Conventional NNP could be measured as consumption plus the value of net addition to manmade capital (net investment). If the environmental resources (air, water, and forests) are considered as natural capital, net investment includes the value of decline in natural capital goods. Shadow prices of natural capital have to be obtained for valuing the changes in natural capital stocks for defining a correct measure of NNP. A correct measure of NNP as shown below incorporates the current loss in value of natural resource stocks due to the use of environmental resources[6]. The accounting prescription for measuring NNP taking the renewable (environmental) resources as natural capital is described below:

Consider an economy producing a commodity X_t using capital stock K_t, and labour L_t, The production function of X_t is given by:

$$X_t = F(K_t, L_t). \qquad (A.1)$$

F is concave and an increasing and continuously differentiable function of each of its variables. Let C_t represent aggregate consumption at time t, and E_t and M_t represent respectively, emissions and the pollution abatement expenditure in the production of X at time t. The net accumulation of physical capital therefore satisfies the condition:

$$dK / dt = F(K_t, L_t,) - C_t - M_t \,. \qquad (A.2)$$

Let S_t represent the stock of environmental resources (quality of water resources or atmosphere) at time t, $N(S_t)$ the natural rate of regeneration of this stock (natural rate of assimilation of pollution loads), and E_t, the rate of depletion of stock (rate of degradation of environmental quality). Therefore, the net accumulation of the stock of environmental resources satisfies the condition:

$$dS_t / dt = N(S_t) - E_t + A_t \,, \qquad (A.3)$$

6 For the details see Hartwick (1990); Maler (1991), Dasgupta and Maler (1998) and Murty and Surender Kumar (2004).

where A_t is the rate of pollution abatement. The pollution abatement cost function is given as $M_t = M(A_t)$

Assuming that the utility depends on the change in stock of the environmental resource, the inner-temporal utility function in the utilitarian form is given as:

$$\int_0^{\infty} U(C_t)\, e^{-rt}\, dt, \qquad \text{(A.4)}$$

where U is strictly concave, increases in C and r is the rate of discount. Consider the planning problem of the government consisting of variables, C, L, A, K, and S. Given the initial stocks of man made capital and natural capital, K_0 ans S_0, the planning problem is feasible if it satisfies conditions (A.1) to (A.3).

The planning problem is:

$$\text{Maximize} \int_0^{\infty} U(C_t, L_t)\, e^{-rt}\, dt, \qquad \text{(A.5)}$$

subject to the constraints (2.2) and (2.3).

The control variables of this optimization problem are C_t, L_t, and A_t while the state variables are K_t, and S_t.

The Hamiltonian of this maximization problem is:

$$H(t) = U(C_t) + p_t\{F(K_t, L_t) - C_t - M_t\} + q_t\{N(S_t) - E_t + A_t\} \qquad \text{(A.6)}$$

where p(t), and q(t) are co-state variables. The canonical equations for this optimization problem are:

$$U_C = p_t \qquad \text{(A.7a)}$$

$$-U_L = p_t\, F_L = w \qquad \text{(A.7b)}$$

$$p_t\, dM / dA = q_t \qquad \text{(A.7c)}$$

$$F(K_t, L_t) - C_t - M_t = 0 \qquad \text{(A.7d)}$$

$$N(S_t) - E_t + A_t = 0 \qquad \text{(A.7e)}$$

$$dp / dt = -\delta H / \delta K_t \qquad \text{(A.7f)}$$

$$dq / dt = -\delta H / \delta S_t\,. \qquad \text{(A.7g)}$$

Transversality conditions

$$\lim_{t \to \infty} p_t = 0 \qquad \text{(A.7h)}$$

$$\lim_{t \to \infty} q_t = 0\,. \qquad \text{(A.7i)}$$

From (A.7b) we have

$$dM / dA = q_t / p_t \tag{A.8}$$

Equation A.7a implies that along the optimal path the price of consumption is equal to its marginal utility while Equation A.7b implies that the market wage is equal to the value of marginal productivity of labor. Equation A.7c shows that the industry carries pollution abatement upto the level at which the marginal cost of abatement is equal to the price it has to pay for the waste disposal services. Equation A.8 shows that the marginal cost of abatement of pollution is equal to its shadow price. Using Euler's theorem, it could be written that:

$$U(C_t , L_t) = U_c C_t + U_L L_t . \tag{A.9}$$

Therefore, equation (2.6) could be written as:

$$H_t = U_c C + U_L L + p \dot{K} + q \dot{S} . \tag{A.10}$$

Taking consumption as numeraire and using equation (A.8), equation (A.10) could be written as:

$$H_t = C + \dot{K} + U_L L / p_t + M' . \dot{S} . \tag{A.11}$$

The first three components on the right hand side of Equation A.11 constitute the conventional national income. The fourth component is the product of change in the environmental resource stock (pollution) and the marginal cost of pollution abatement. That means, the marginal cost of pollution abatement is the shadow price of pollution. If dS / dt is less than zero meaning that the environmental quality falls with the economic development, Equation A.11 shows that the pollution abatement cost has to be deducted from the NNP to get environmentally corrected NNP (ENNP). Alternatively, the shadow price of pollution could be interpreted as the marginal welfare gain from the pollution reduction as given in the right hand side of Equation A.8.

2.3 Use of Exhaustible Resource as a Source of Pollution: The CO_2 Problem

The above model provides an accounting principle for measuring ENNP when a renewable environmental resource is used. There could be cases in which use of an exhaustible resource results in the use of renewable environmental resource. The CO_2 problem is one among such cases. Use of fossil fuels for production and consumption results in the depletion of exhaustible resources and the pollution of environment from the burning fuels. Assume that an exhaustible resource such as coal or oil, say Y_t is used in the production of X_t apart from capital and labor and the pollution load E_t is proportional to the resource Y_t used. That means $E_t = \alpha Y_t$ where α is the ratio of pollution load to the amount of resource used.

The production function of X_t is given by:

$$X_t = F(K_t, L_t, Y_t). \qquad \text{(A.12)}$$

F is concave and an increasing and continuously differentiable function of each of its variables. Let C_t represent aggregate consumption at time t, and E_t and M_t represent respectively, emissions and the pollution abatement expenditure in the production of X at time t. The net accumulation of physical capital therefore satisfies the condition

$$dK / dt = F(K_t, L_t,) - C_t - M_t - vY_t , \qquad \text{(A.13)}$$

where v is the price per tonne of coal.

Let R_t represent the stock of exhaustible resource, say coal. The rate of depletion of this stock, if fresh discoveries of the resource are not there, is given by

$$dR / dt = - Y_t . \qquad \text{(A.14)}$$

Let S_t represent the stock of environmental resources (quality of water resources or atmosphere) at time t, and $N(S_t)$ the natural rate of regeneration of this stock (natural rate of assimilation of pollution loads). Therefore, the net accumulation of the stock of environmental resources satisfies the condition,

$$dS_t / dt = N(S_t) - \alpha Y_t + A_t , \qquad \text{(A.15)}$$

where A_t is the rate of pollution abatement. The pollution abatement cost function is given as $M_t = M(A_t)$.

Assuming that the utility depends on the change in stock of the environmental resource, the inter-temporal utility function in the utilitarian form is given again as in equation (2.5).

The Hamiltonian of this maximization problem is:

$$H(t) = U(C_t , L_t) + p_t \{F(K_t, L_t ,Y_t) - C_t - M_t - vY_t\} + q_t\{N(S_t) - \alpha Y_t + A_t\} + r_t (-Y_t) , \quad (A.16)$$

where p(t), q(t), and r_t are co-state variables. The canonical equations for this optimization problem are:

$$U_C = p_t \quad (A.17a)$$

$$-U_L = p_t F_L = w \quad (A.17b)$$

$$p_t (F_y - v_t) - \alpha q_t = r_t \quad (A.17c)$$

$$p_t M^{/} = q_t \quad (A.17d)$$

From (17d) we have

$$M^{/} = q_t / p_t \quad (A.18)$$

and from (A.17c) and (A.17d) we have : $r_t = ((F_y - v_t) - \alpha M^{/})) p_t$. (A.19)

By the linear approximation of the utility function U, the Hamiltonian in A.16 could be written as:

$$H_t = U_C C_t + U_L L_t + p_t \dot{K}_t + q_t \dot{S}_t + r_t \dot{R}_t . \quad (A.20)$$

Taking consumption as numeraire and using equations A.18 and A.19, A.20 could be written as:

$$H_t = C_t + U_L L_t / p_t + \dot{K}_t + M^{/} \dot{S} + \{((F_y - v_t) - \alpha M^{/})\} \dot{R}_t . \quad (A.21)$$

The first four components are the same as those in equation A.11. The term $\{((F_y - v_t) - \alpha M^{/})\}$ in the equation could be interpreted as the generalized Hotelling rent on the fossil fuels after accounting for the cost of abatement of pollution arising out of use of the resource. By using say one tonne of fossil fuel, α tonnes of pollution is generated and the cost of abatement of it is $\alpha M^{/}$ which has to be accounted for in defining the Hotelling rent. It is so because the cost of depletion of environmental quality due to pollution evaluated at the shadow price, the marginal cost of pollution abatement, is already accounted in measuring ENNP through the fuorth component in Equation A.21.

Appendix B

Air Quality Modeling

Consider an air shed or system of waterways in which there are *m* sources of pollution, each of which is fixed in location. Also there are n receptor points in the water shed at which ambient water quality is monitored. Ambient environmental or water quality is defined in terms of pollutant concentrations say BOD concentration at each of *n* receptor points in the water shed. It implies that we can describe water quality by a vector $Q = (q_1, \ldots, q_n)$ whose elements indicate the concentration of the pollutant at each of the receptors. The dispersion of effluents containing BOD from the *m* sources is described by an $m \times$ n matrix of unit diffusion (or transfer) coefficients:

$$D = \begin{bmatrix} & \vdots & \\ \cdots & d_{ij} & \cdots \\ & \vdots & \end{bmatrix}$$

where the element d_{ij} indicates the contribution that one unit of emissions from source *i* makes to the pollutant concentration at receptor point *j*. Given this matrix, we can write the relationship between the pollution at m sources and the ambient air quality at n monitoring points in the watershed as

$$ED = Q \ , \qquad \text{(B1)}$$

where $E = (e_1, e_2, \ldots\ldots\ldots e_m)$ is a vector of emissions at m sources in the water shed. Equation B1 shows that given the ambient water quality standards at different monitoring stations in the watershed the corresponding pollution loads say in tonnes of BOD could be found out and these could be treated as source-specific standards.

The environmental objective is to attain some predetermined level(s) of pollutant concentrations within the watershed given as $Q^* = (q_1^*, \ldots, q_n^*)$. If there are markets for pollution permits in the watershed, trading in pollution permits between the sources could result in the cost minimizing levels of emissions at all sources for achieving the given ambient pollution standards (Baumol and Oates, 1994). There also will be an equilibrium pollution permit price which is equal to the marginal cost of pollution abatement for all the sources. This marginal cost pollution abatement is the shadow price of pollution for estimating the monetary value of water quality changes in the watershed during an accounting period. This shadow price is water shed specific and there could not be one price for the country as a whole given that it does not make any sense of having trading pollution permits across the watersheds.

References

Baumol, W.J. and Wallace E. Oates (1994), *The Theory of Environmental Policy,* Cambridge University Press.

Christensen, P.P. (1989), Historical Roots for Ecological Economics-Biophysical Versus Allocative Approache*, Ecological Economics.* Vol. 1, pp. 17-36.

Daly, H. (1990), Commentary: Toward some operational principles of sustainable developmen, *Ecological Economics,* Vol. 2, pp 1-6.

Dasgupta, P. and K.G. Maler (1998), Decentralisation Schemes, Cost-Benefit Analysis, and Net National Product as Measure of Social Well Being*, The Development Economics Discussion Papers Series No.12, LSE, STICERD.*

Freeman, III, A.M. (1993*), The Measurement of Environmental and Resource Values: Theory and Methods,* Washington D. C: Resources for the Future.

Hartwick, J. M. (1977), Intergenerational Equity and the Investing of Rents from Exhaustible Resources*, American Economic Review.* Vol. 66, pp. 972-974.

Hartwick, J. M. (1978a), Investing Returns from Depleting Renewable Resources and Intergenerational Equity, Economics Letters. Vol. 1, pp. 85-88.

Hartwick, J. M. (1978b): Substitution Among Exhaustible Resources and Intergenerational Equity, *Review of Economic Studies*. Vol. 45, pp. 347-354.

Hartwick, J. M (1990). Natural Resources, National Accounting and Economic Depreciation, *Journal of Public Economics*, Vol. 43, pp. 291-304.

Klassen, G., and H. Opschoor (1991), Economics of Sustainability of Economics, *Ecological Economics*. Vol.4, pp. 83-92

Maler, K.G. (1991), National Accounts and Environmental Resources*, Environmental and Resource Economics.* Vol.1, pp. 1-15.

Mitchell, R. C. and R. T. Carson, (1989), "Using Surveys to Value Public Goods: The Contingent Valuation Method", Resources for the Future, Washington D.C.

M.N. Murty et al. (2006), Social Cost-Benefit Analysis of Delhi Metro, *IEG Working Paper Series,* E/273/06, Institute of Economic Growth, New Delhi.

Murty, M.N., S.C. Gulati (2005), A Generalized Method of Hedonic Prices: Measuring Benefits From Reduced Urban Air Pollution. *IEG Working Paper Series,* E/254/06, Institute of Economic Growth, New Delhi.

Murty, M.N., S.C. Gulati, and A. Banerjee (2003), Hedonic Property Prices and Valuation of Benefits from Reducing Urban Air Pollution in India, *Working paper no. E 237/2003, Institute of Economic Growth, Delhi.*

Murty, M.N. and Surendar Kumar (2004), *Environmental and Economic Accounting for Industry*, New Delhi, Oxford University Press.

Murty, M.N., Surender Kumar and Kishore K. Dhavala (2006), Measuring Environmental Efficiency of Industry: A Case Study of Thermal Power Generatio in India, *IEG Working Paper Series*, E/270/06, Institute of Economic Growth, New Delhi.

Pearce, D.W et al. (1989), *Blue Print for a Green Economy,* Earthscan: London.

Pearce, D.W., and R.K. Turner (1990), *"Economics of Natural Resources and the Environment",* Hemel Hemstead-Harvester-Wheatsheaf.

Samuelson, P. (1961), The Evaluation of Social Income: Capital Formation and wealth, *In the Theory of capital, Proceedings of an IRA conference,* Lutz and Hague, eds., Newyork, St. Martin's Press, 1961.

Solow, R.M. (1974), The Economics of Resources or the Resources of Economics, *American Economic Review,* Vol. 64, pp. 1-14.

Sudhakar Yedla et. al (2002), *Air Quality Modeling: Case Studies of Delhi and Mumbai,* Indira Gandhi Institute of Development Research, Mumbai.

Sushmita Chatterjee et. al (2006), Estimating Cost of Air Pollution Abatement for Road Transport in India: Case Studies of Andhra Pradesh and Himanchal Pradesh, forthcoming in *Economic and Political Weekly.*

UN (1993), *Integrated Environmental and Economic Accounting*, Interim version (Sales No. E93 XVII. UN 12), New York, United Nations.

Weitzman, M. (1976), On the Welfare Significance of National Product in a Dynamic Economy, *Quarterly Journal of Economics,* Vol. 90, pp.156-162