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Review of linked modelling of low-carbon development, mitigation and its full costs and benefits

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Developing countries exploring pathways to climate compatibility

Review of linked modelling of low-carbon development, mitigation and its full costs and benefits

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EXECUTIVE SUMMARY

Low carbon development refers to long-term socio-economic transformation that is compatible with the ultimate objective of the UNFCCC to stabilize GHG concentrations. Different types of models have evolved to assess alternate futures and delineate cost-effective GHG emissions mitigation measures at national, regional, and global levels. Mitigation policymaking happens at global, national, local and sectoral levels. Policy objectives and perspectives vary at each level. Global policymakers aim at long-term climate stabilization; national policymakers give priority to align national goals like energy security and access with global climate policy signals; local policymakers seek opportunity to use national mitigation policies with issues like air quality; and the sector players are interested in implications on competitiveness and employment.

Model architectures and modelling approaches therefore differ depending on the type of questions they address; their spatial, temporal and sectoral focus; the costs, benefits and risks included; and the types of mitigation policies being assessed. A model, besides being a purposive computational device used by analysts; is essentially a communication tool that elucidates the information and enhances understanding between scientists, policymakers and other stakeholders.

A first step for selecting a model is to identify the key policy questions that need to be addressed. Often, a suite of aptly linked models is required to coherently address multiple, but linked, policy questions. Models are formal, transparent and verifiable tools of communication; the best-use choice is with the user.

The bulk of GHG emissions emanate from the energy sector. Hence, significant mitigation modelling efforts are focused on the energy system. Sizable modelling assessments are devoted to other key GHG emitting sectors; e.g. agriculture, forestry and land-use changes.

Energy models are differentiated on the basis of their economic rationale, disaggregation, temporal dynamics, geographic and sectoral coverage, aims and questions, degrees of endogenization and the underlying mathematical techniques. The models either predict the future trends or explore and assess different futures. The modes are classified as top-down (macro-economic), bottom-up (techno-economic or accounting) or linked models (soft-linked or hybrid) and integrated assessment models.

The modelling assessments aim to assist policymakers using best available knowledge and tools. The scenarios are used as the key constructs for articulating the future dynamics. Scenario analysis 'projects' the trends in alternate futures; as opposed to the conventional assessments that aim to 'predict' or forecast the future. The policy assessments use two approaches; the conventional forecasting approach and the back-casting approach wherein the models aim to reach multiple objectives, including the climate goal, and thereby delineate policies and measures that optimize full costs and benefits.

The global climate change policymakers have varied concerns, e.g. assigning responsibility of the past emissions behaviour; overcoming the behavioural, technological and institutional lock-ins inherited from the past; agreement by the nations on the long-term GHG concentration stabilization target; distributing, among the nations, the total costs of mitigation and adaptation actions and the impacts of residual climate change in a fair and equitable manner; following the 'precautionary principle' and the principle of 'intergenerational equity' to avoid passing the climate change burden to the future generations.

National policymakers have wide-ranging economic concerns regarding low carbon development. Typical of these are the implications the greenhouse gas mitigation policies and measures would have on energy security, energy access, incremental job creation and poverty.

The greenhouse gas mitigation problem links the local policy issues directly with the global socio-economic and environmental policy dynamics. For instance, the low carbon development generally has positive effects on air quality in cities. However, the increase in price of kerosene, a fuel used by the poor for cooking and lighting, could worsen the indoor air quality if traditional biomass replaces kerosene.

Models are supported by strategic databases which contain information such as future technology trends, resource constraints and the demographic and economic trends which are key drivers of GHG emissions. Modelling assessments are based on numerous assumptions about the drivers of alternate futures (scenarios) and a set of policy objectives or aims. The choice of modelling parameters depends primarily on objectives; the specific parameter choices depend on the real-life constraints as well as the type of model being used.

The review of low carbon development studies show a great deal of heterogeneity in terms of:

- i) use of models,
- ii) scenarios assumptions,
- iii) policy objectives,
- iv) choice of socio-economic, resources and technology parameters, and
- v) modelling approaches.

There are a few studies which link top-down models with bottom-up models. Sectoral models are used in key GHG emitting sectors like electricity, energy intensive industries, agriculture, forestry and land-use. In some cases, sectoral models are linked to an economy-wide model so as to receive the feedback from aggregate economy-wide signals which may alter competitive dynamics of the sector or provide key insights into the sector specific GHG mitigation measures.

Several modelling studies in developing countries follow a 'low carbon society' approach. These studies use soft-linked models which connect and align the global stabilization targets to national and local dynamics, objectives and constraints along the geographical hierarchy linking the global to the local scale.

The scenarios data and model related parameters can be shared among models that follow a similar paradigm and scope of the assessment. However, the heterogeneity of the models, modelling approaches and scenario specifications create a huge demand for diverse data. The heterogeneity results in low comparability of modelling results across studies. The global modelling community has moderately succeeded in overcoming these lacunae by sharing common modelling protocols across studies undertaken by different modelling teams.

An important cooperative modelling exercise for long-term transition to robust and carbon efficient economies is organized under the Mitigation Action Plans and Scenarios (MAPS) project¹ and The Climate and Development Knowledge

¹ See www.mapsprogramme.org for more information

Network (CDKN)² Linking Project. Five modelling teams - COPPE Brazil, EC Chile, UniAndes Colombia, IIAP Peru and ERC South Africa - are working as partners on the project.

The comparative assessment of modelling approaches in the MAPS and CDKN Linking Project demonstrates the diversity of policy issues in developing countries that are posed to the modelling assessments; the variety of models and modelling approaches needed to address these issues; the need for modelling capacity building; and the value of shared databases and sharing of modelling experiences among the developing countries.

Model applications are diverse and most focus at the national level, e.g. impact of global carbon price, impact of plug-in hybrid electric vehicles (PHEV), future cost of electricity supply, assessment of sectoral energy demand, impact of sectoral tariff variation on national economy, impact of land-use change on agriculture, cost of GHG mitigation for agro- forestry and forest plantations, estimation of future investment in energy sector.

The diversity of models used by modelling teams arise since model choices depend on the policy questions posed and the familiarity and capacity of a national modelling team vis-à-vis use of specific models. The MAPS and CDKN Linking Project demonstrates the urgent need and immense value of capacity building for policy modelling in developing countries.

² see www.cdkn.org for more information

1. MODELLING OF LOW CARBON DEVELOPMENT: AN INTRODUCTION

Low carbon development refers to long-term socio-economic transformation that is compatible with stabilization of GHG concentrations in the atmosphere at a level that will prevent dangerous anthropogenic interference with the climate system. The United Nations Framework Convention on Climate Change (UNFCCC), the key global institution established to limit the GHG emissions and the impacts from residual climate change, exhorts that the measures to deal with climate change should be *cost-effective so as to ensure global benefits at the lowest possible costs*. In accordance, the models have evolved to assess alternate futures and to delineate cost-effective policies and measures to mitigate GHG emissions at national, regional, and global levels.

There are varied modelling approaches; each focusing on answering a suite of questions related to low carbon development. The aptness of a model for an assessment depends on varied factors – such as time horizon; extent of regions covered; types of emissions sources included; extent of trade permitted; types of technologies and resources included; the extent of costs, benefits and risks being covered and the types of policies and mitigation actions to be delineated. The model architecture, its underlying paradigm, database and the modelling approach depend on the aim of the modelling exercise. The selection of a model and the assessment method therefore follow the ‘horses for courses’ principle.

Integrated Assessment Modelling studies assess full costs and benefits associated with mitigation and adaptation actions and the impacts from the residual climate change. Most of the mitigation modelling exercises however follow a cost-effectiveness paradigm; i.e. they assess full costs of mitigation and associated co-benefits (and co-costs and risks) but do not explicitly include costs of impacts and adaptation related to residual climate change. The socio-economic transformation in a nation needs to address numerous issues besides climate change. Sustainable development is a paramount theme that aligns local and national development goals with global climate change actions. The modelling studies, normally using the ‘*back-casting*’ methodology, showing that mainstreaming climate actions within development plans delivers numerous co-benefits such as enhanced energy; food and water security; Improved energy access and air quality; reduced climate change risks and lower ‘*social cost of carbon*’ (Shukla and Dhar, 2010). The opportunities to gain such multiple dividends abound everywhere, and more so in developing nations. This approach places sustainable development as central to addressing the global climate change problem. It offers a cooperative, rather than polarized, way of meeting the challenges of global climate change.

Most mitigation models follow long time horizons; ranging from the year 2030 to 2100. The approach for long-term assessments is to make the ‘*projections*’ and not the predictions. The modelling studies examine scenarios; the storyline of each articulating an alternate future. The assessment of alternate futures helps to delineate robust policies and actions, e.g. those which are part of the cost-effective options in majority of scenarios. Modelling is thus vital for developing low carbon development plans and strategies that are consistent with national circumstances. Models identify the mitigation policy instruments and measures needed for GHG abatement; the optimal pecking order of feasible policy choices in the near and long term to achieve the desired target of climate stabilization.

Since there are numerous modelling approaches and models available to answer different policy questions; the first step before finding the appropriate model is to identify the key policy questions that need to be answered. Since no single model can address all questions of varied stakeholders; it is vital to have a good understanding of each type of model and the modelling approach; its advantages and limitations. Often, a suite of aptly linked models is used to coherently address diverse and multiple questions. Models, besides being purposive computational devices, are in essence communication tools that bridge the information gap and enhance understanding among scientists, policymakers and other stakeholders. Below is a review of linked modelling of low-carbon development, mitigation and its full costs and benefits.

2. MODELLING DOMAINS AND KEY POLICY CONCERNS

Low carbon development is a universal and pervasive issue. Policy-making therefore spans across all spatial, temporal and sectoral domains (Figure 1). The modelling covers all policy related issues and aspects of these domains. The bulk of GHG emissions arise from the energy sector and land-use change and hence these find specific emphasis in low carbon development modelling.

The long-term, in case of climate change policy-making, spans 100 years in the future since the GHG emissions have a long life time in the atmosphere (e.g. over 100 year for CO₂) and the capital stocks or the physical assets of the key GHG emitting sectors (e.g. energy) have long turnover time. The spatial scale ranges from global to local. GHGs are long-lived and well-mixed gases in the atmosphere and hence their warming effect is independent of their spatial origin on the globe. On the other hand, the GHG emissions arise from multitude of human activities happening at all locations such as in homes, transport vehicles, agriculture fields and industries.

Typically, the greenhouse gas mitigation policies are framed along and across the domains. For instance, a national policymaker belonging to a transport ministry could engage in long-term policy like investment in rail infrastructures. In which case, the analysts supporting the policymaking shall consider a model that has capability to handle:

- i) detailed specifications of transport sector,
- ii) global or national level macro-economic or techno-economic dynamics, and
- iii) capability for long-term scenario assessment.

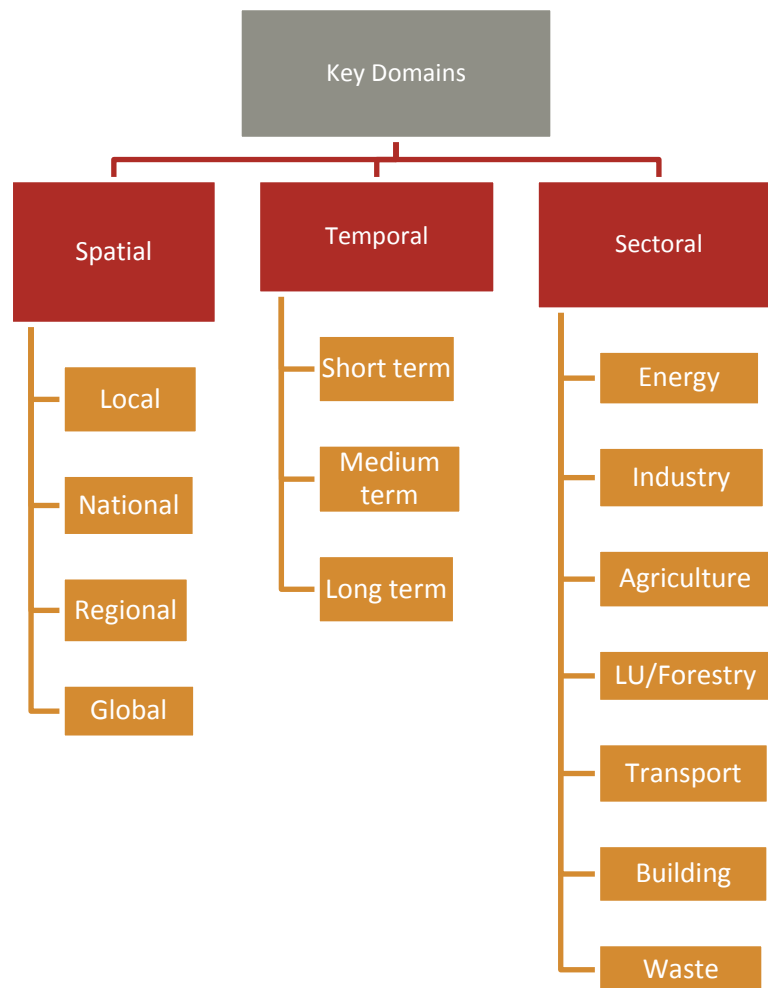


Figure 1: Key Modelling Domains – Spatial, Temporal and Sectoral

Human activities have underlying socio-economic purpose. They make positive contributions, but often have unintended negative effects. The policy concerns for mitigating greenhouse gas emissions hence differ across the domains. Specific policy concerns in different spatial and sectoral domains are as under.

2.1. Global Policy Concerns: Climate Change

Climate change is an extreme case of externality arising from the conventional development pathway. Its implications are extreme in the dual sense: they are global and long-term. At the political process level, the global climate change policy concerns include:

- i) assigning responsibility of the past emissions behaviour;
- ii) overcoming the behavioural, technological and institutional lock-ins inherited from the past socio-economic behaviour;
- iii) agreement by the nations on the long-term GHG concentration stabilization target;
- iv) distributing, among the nations, the total costs of mitigation and adaptation actions and the impacts of residual climate change in fair and equitable manner; and

- v) following the '*precautionary principle*' and the principle of '*intergenerational equity*' to avoid passing the climate change burden to the future generations.

In terms of practical policymaking, the global policy tasks include: first, agreeing to the protocol which puts the global GHG emissions trajectory on the 2°C stabilization pathway; second, devising policy instruments and measures to achieve the stabilization target in the most cost-effective manner permitted by the national circumstances. The integrated assessment models (discussed in section 3) are best suited to address the climate policy concerns as well to delineate these tasks.

2.2. National Policy Concerns

National policymakers have varied economic concerns vis-à-vis low carbon development. Typical of these are the implications the greenhouse gas mitigation policies and measures would have on energy security, energy access, incremental job creations and impact on poverty.

From the national perspective, energy security is a multifarious and aggregate concept of risk. The aggregate national energy security risk is viewed from energy supply perspective and is measured as the percentage value of energy imports over the aggregate energy use in the national economy. The energy security acknowledges that there are multiple forces which create risks in energy transactions and the aggregate risks have to be minimized by a coordination process and the residual has to be shared. Alternatively, energy security is defined as sufficient supplies of energy at an affordable price (Yergin, 2006). GHG mitigation can adversely affect energy security in nations who own sizable fossil energy resources.

Greenhouse gas mitigation policies would increase the relative price of fossil fuels compared to, for instance, the renewable or nuclear technologies. Since fossil energy industries, like coal mines, support large number of jobs, any reduction in the demand for fossil fuels would reduce the employment. The question remains as to whether low or zero carbon energy industry can create more jobs than what are lost in the fossil sector.

Higher price of fossil fuels, resulting from quantitative limitation on carbon emissions or the carbon tax may also ill-affect energy access by the poor. The competition for land and water by bio-energy may increase food and water insecurity in nations having land and water shortages.

The development challenges related to energy security, energy access, poverty alleviation, health, gender equity, and employment are more pertinent in developing nations. Slow pace and misdirected development would also hinder the adaptive capacity of these countries (IPCC, 2007). Soft-linked global and national modelling systems (discussed in section 3) are well suited to examine such issues and inform policymakers about the implications of low carbon development on key socio-economic indicators.

2.3. Local Concerns

The net effect of low carbon development on air quality is generally positive. Reduced consumption of fossil fuels helps improve air quality, e.g. in cities. However, the increase in price of kerosene, a fuel used by the poor for cooking and lighting, could worsen indoor air quality if traditional biomass replaces kerosene. The deterioration of indoor air quality in poor households adversely affects women and children who have greater exposure to polluted air.

In case of large point sources of pollution, like coal power plants or steel plants, there are opportunities for conjoint emissions mitigation, e.g. for CO₂ and SO₂ (Menon-Chaudhury and Shukla, 2009; Menon-Choudhury et. al. , 2007). The conjoint emissions trading regimes for such associated pollutants can reduce the overall costs of mitigation. The techno-economic energy system models are well suited to analyze such benefits of such conjoint mitigation opportunities. The modelling of local air quality scenarios requires converting emissions into concentrations of pollutants. This needs an interdisciplinary approach involving economists (for articulate socio-economic pathways), engineers (for technologies) and meteorologists (for weather interactions).

Conventionally, the policy studies to mitigate local pollution *follow inventory approach*; i.e. they focus on inventories of different gases. The bottom-up techno-economic models, e.g. ANSWER-MARKAL, TIMER, LEAP, AIM End-use (see Shukla et. al., 2009; Rafaj and Kypreous, 2007; Van ruijven et. al., 2011), have been used for assessing emissions from energy sector. The models permit following the *impacts approach* which links the entire chain, i.e. drivers of polluting activities, amount of pollution, the concentrations of pollutants in the air (i.e. air quality), impacts of air quality on human and natural systems and the assessment of policies to mitigate the air quality and GHGs.

The transformation from pollutant loads to pollutant concentrations are made using atmospheric dispersion models. RAINS model (Alcamo et. al., 1990) is a good example of an integrated assessment model and was used extensively during the negotiations process for the second sulfur protocol and convention on long range trans-boundary air pollution (Cofala and Syri, 1998). A number of modelling studies in developing countries have made use of models that use the impacts approach to study the pollutant concentrations for past (Guttikunda et. al., 2013; Guttikunda and Calori, 2013) and also link them to the health costs (Li et. al., 2004).

2.4. Sectoral Concerns

The low carbon development and related mitigation policies and measures have varied effects on the sectors in terms of technology selection, pricing of outputs and competition. The most studied sector is the energy supply sector wherein the competition among fuels and technologies are altered significantly by the change in their relative prices through low carbon development policies. The national policymakers are also deeply concerned for those industry sectors which have high emissions incidence and are exposed to global competition.

In the transport sector, vehicle efficiency, modal shifts and design of urban forms are key concerns at national and city levels. The competition concerns are raised by low carbon policies for international aviation and shipping. The case in point is the EU proposal for imposing carbon tax on intercontinental flights landing and taking-off from EU territory. In demand energy sectors like the buildings, the policies are focused on appliance efficiency and building codes which ensure low energy use.

There are two paradigms for sector level mitigation assessments. The first approach is to use a comprehensive model of the economy which includes all sectors; but within this, the sector whose policies are to be assessed is represented in greater depth. Advantage of this approach is that the interactions of the sector policies with other sectors of the economy are examined endogenously. The second approach is to use a sector specific model and then interface the dynamics of the rest of the economy exogenously through scenario specification and then interpret the results in the overall and macro contexts.

3. MODELLING PARADIGMS

Modelling approaches have evolved over past two decades to address policy questions related to low carbon development and identify the roadmap of mitigation actions. Energy systems contribute the bulk of the GHG emissions now and will continue to do so in future (IPCC, 2007). Significant modelling efforts are hence focused on the energy sector, which is also the focus of this paper. This aside, there is significant modelling work devoted to assessing mitigation roadmap for other key GHG emitting sectors like agriculture, forestry and land-use changes.

The energy models are differentiated in multiple ways (Loulou et. al.,2004; Hourcade et. al.,1996; Grubb et. al.,1993; IPCC, 2001; Rivers and Jaccard, 2006; Shukla et.al.2004; Hedenus et.al., 2012) such as based on:

- (i) economic rationale,
- (ii) level of disaggregation of decision variables,
- (iii) time horizon and temporal dynamics,
- (iv) geographic coverage,
- (v) sectoral coverage,
- (vi) aim of the model,
- (vii) degrees of endogenization, and
- (viii) underlying mathematical techniques.

Three key purposes of models are:

- i) to predict or forecast the future trends,
- ii) to explore the future, and
- iii) to assess the feasibility of desirable futures (Hourcade et. al. 1996).

The full costs and benefits of low carbon development and mitigation from the energy sector are estimated using two approaches, namely top-down (macro-economic) or the bottom-up (techno-economic) (Figure 1). The division into these two categories is not exhaustive and there are hybrids models which include features of both approaches. Beyond these, there are integrated assessment models (IAMs) which integrate all sectors of the economy, though hard or soft-linking of multiple models.

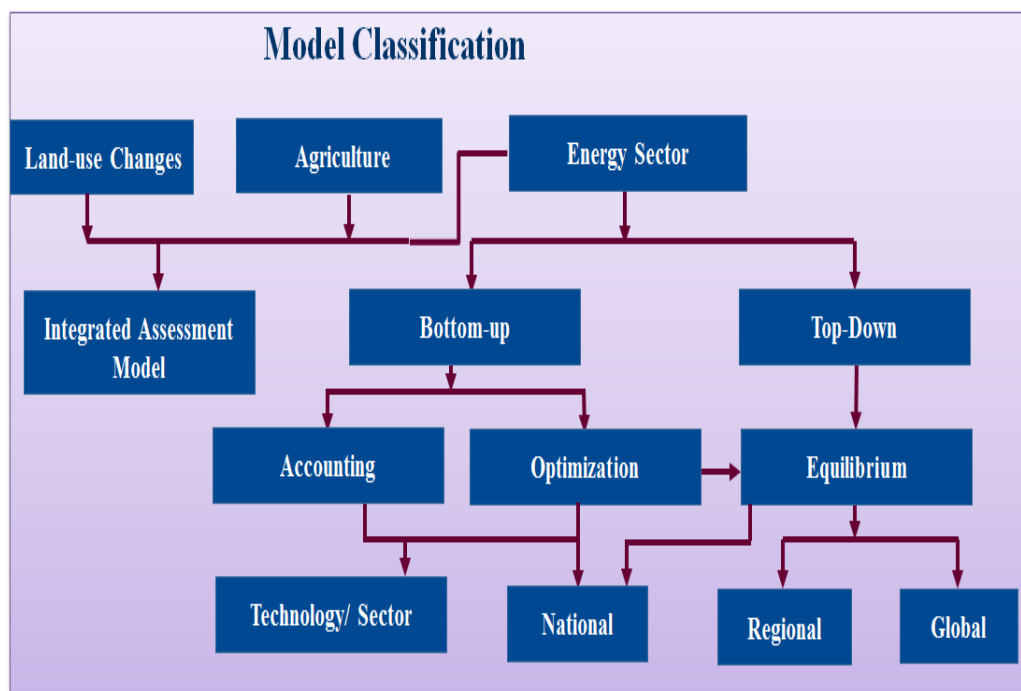


Figure 2: Model Classification

3.1. Top-Down (Macro-economic) Models

Top-down models make aggregate representation of the economy; they endogenize economic effects, have none or limited characterization of technologies and reflect the ‘pessimism’ inherent in the economic models (Grubb et. al., 1993). These models are well suited to assess the economic cost and environmental effect of energy and environment policies, especially the market oriented policies such as carbon tax, tradable quota and feed-in tariffs, at national and global scales (Ciscar et. al., 2013; Massetti and Tavoni, 2012; Xu and Masui, 2009; Remme and Blesl, 2008). The time-horizon for the carbon mitigation analysis using top-down models generally span thirty to one hundred years.

The top-down models are based on computable general equilibrium theory. The underlying economic structure of these models rests on input-output tables. The data for the base year is calibrated from past economic trends. The model has only monetary flows and there are no physical flows of energy or other commodities. The dynamic equilibrium of the model delivers commodity prices; one price corresponding to each sector represented in the model. The quantification of a commodity in physical units, e.g. energy, is done by dividing the total economic output of the sector by the price.

These models assume perfect market equilibrium conditions throughout. The policy interventions, e.g. low carbon development and GHG mitigation policies, shift the state of the general equilibrium. After a policy intervention (e.g. tax or subsidy), the equilibrium is regained through price adjustments and agents (firms, household, government) trying to maximize their own welfare under constrained conditions through quantity adjustments. A few modellers, who wish to be closer to the reality, have attempted to develop ‘macro-economic’ top-down models which permit imperfect competition (Hourcade et.al. 1996; Springer, 2003). Some commonly used top-down models for carbon mitigation analysis are listed in Table 1.

TABLE 1: TOP-DOWN MODELS WIDELY USED FOR CARBON MITIGATION ANALYSIS

Model	Institution	Theoretical Framework
AIM/ CGE	NIES, Japan	General equilibrium
MERGE	EPRI, US	General equilibrium
GTEM	ABARE, Australia	General equilibrium
EPPA	MIT, US	General equilibrium
OECD-ENV-LINKAGES	OECD	General equilibrium
PACE	ZEW GmbH Centre for European Economic	General equilibrium
EPPA	MIT, US	General equilibrium
E3MG	Cambridge, UK	Macro- Economic

3.2. Bottom-up Models

Bottom-up models are based on techno-economic perspectives and are built on a disaggregated sector level representation of the economy. They include detailed characterization of technologies and reflect the optimistic engineering view of technological progress (Grubb et. al., 1993). Bottom-up models are normally used for national and regional level mitigation assessment with primary focus on the energy sector (Chiodi et.al., 2013; Zhou et.al., 2013; Deetman et.al., 2013; Kesicki, F., 2012 ; McDowall et al., 2012; Hainoun, 2010; Liu et al. ,2009; Winkler et al., 2009, and Shukla, 1995). The time-horizon for the carbon mitigation analysis using bottom-up models generally span thirty to fifty years. The bottom-up models follow two kinds of computational frameworks: optimization and accounting.

Optimization models use solution techniques, like linear programming, which find discounted least cost solutions for delivering an energy system which meets the energy demands of economic sectors and also satisfy various techno-economic constraints. The optimization models, e.g. MARKAL (Loulou et. al. 1997), follow a partial equilibrium approach with a focus on the energy sector assuming that other sectors are not affected by changes in energy demand or the way this demand is serviced.

Optimization models are further differentiated based on the solution approach (Barbiker et.al, 2009; Hedenuset.al, 2012). Some optimization models like MARKAL and TIMES assume perfect foresight, i.e. the economic agents have rational expectation about all relevant future information at the time of decision making. Some other models, e.g. AIM-Enduse model, assume agents have myopic expectations. These models are also called dynamic recursive models. Their investment and consumption decisions are made taking into consideration the prices which prevail in the current time period.

Accounting models are driven by exogenous assumptions about the energy demand by sectors and supply of energy resources. They do not attempt to endogenously achieve any objective. Accounting framework is generally used to carry out simulation of various policy options quickly and hence it is quite useful for communication of the results to the policy makers and stakeholders within a short time frame.. Accounting models are quite suitable for back-casting assessments that delineate a pathway to achieve a set of future goals and targets. These models have high flexibility and can be modified to represent the energy system at any spatial scale (cities, states, countries, regions). The accounting models are able to assess future energy demand and related emissions of the entire energy sector or a subsector (Park et.al, 2012; Shan et.al.2012).

TABLE 2: BOTTOM-UP MODELS WIDELY USED FOR CARBON MITIGATION ANALYSIS

MODEL	INSTITUTION	THEORETICAL FRAMEWORK
LEAP	Stockholm Environment Institute	Accounting Framework
MARKAL	ETSAP	Partial Equilibrium
MESSAGE	IIASA	Partial Equilibrium
AIM-Enduse	NIES, Japan	Partial Equilibrium
TIMER	PBL, Netherlands	Partial Equilibrium
POLES	LEPII-EPE	Partial Equilibrium
PRIMES	National Technical University of Athens	Partial Equilibrium
AIM/EXSS	NIES, Japan	Accounting Framework
2050 Pathway Tool	Dept. of Energy and Climate Change, Japan	Accounting Framework
LBNL China End-use Energy Model	Lawrence Berkeley National Laboratory	Accounting Framework
TIMES	ETSAP	Partial Equilibrium

3.3. Linked Top-Down and Bottom-up Models

Top-down models are short of technological and disaggregated sectoral detail whereas bottom-up models lack macro-economic consistency.

TABLE 3: SHORTCOMINGS AND ADVANTAGES OF BOTTOM-UP AND TOP-DOWN MODELS

MODEL PARADIGM	SHORTCOMINGS	ADVANTAGES
Bottom-up	1. The typical bottom-up approach focuses on the energy system itself and not on the relationship with the economy as a whole (van Vuuren et al, 2009). They tend to be optimistic about technology progress.	1. Bottom-up models are built from disaggregated sector levels. They include detailed characterization of technologies on demand and supply-sides.
	2. Bottom-up models do not have linkages of energy sector with rest of the economy. Hence they cannot capture macro-economic impact of policies that changes in energy prices or trade effects on macro-economy.	2. In bottom-up models, technologies are represented as a transformational relationship between physical inputs and outputs. The models are therefore good evaluate technological progress, e.g. technological learning, in terms of technical parameters.
	3. The optimization models calculated energy prices simultaneously based on energy supply and demand. Prices do not account for economy-wide feedback effects. Optimization models assume existence of a social planner.	3. Optimization models can find shadow prices which reflect scarcity value of resources, e.g. carbon emissions allowances. This framework can provide useful insights in countries which follow the planning model for resource allocations.
	4. Technologies, providing same service are assumed to be perfect substitutes except for their anticipated financial cost estimates. The risks of long payback period, attributes of technologies and consumers' preferences are not taken into consideration.	4. Accounting type models can assess various policy options readily and facilitate policymakers and stakeholders to make quick decisions. Such models are suitable for back-casting of a roadmap of actions to achieve a set of future goals and targets
Top-down	1. Top-down models assume perfect market equilibrium conditions throughout the time span. This assumption too strict in reality as markets is beset with monopolies (e.g. energy markets) and incomplete markets especially in developing nations. .	1. Top-down models endogenize economic effects. Therefore prices of resources, e.g. energy or carbon allowances, reflect economy-wide feedbacks. They follow agent-based, game theoretic framework and do not assume the existence of a social planner.
	2. Input substitution elasticity is usually computed in CGE models based on the historical data and these values are assumed to be valid for future. (Hourcade et.al, 2006; River and Jaccard, 2006). This assumption is invalid in long-term studies.	2. Top-down models are well suited to discover the values of key policy parameters, e.g. price, of market oriented policies such as carbon tax, tradable quota and feed-in tariffs, at national and global scales.
	3. Due to limited representation of technologies, top-down models are unable to assess the effects of technology-oriented policies. Top-down models are not good at representing demand-side technologies. They are pessimistic about technological progress.	3. The aggregate, but comprehensive, representation of the economy permits top-down models to be integrated with models from scientific disciplines. Top-down models are preferred for representing global economic dynamics in the integrated assessment models.
	4. Top-down models cannot estimate benefits gained by non-price policy changes and therefore underestimate the potential of efficient low carbon technologies.	4. Top-down models are well suited for long-term assessment such as spanning a century long time horizon.

In order to address these deficiencies, two strategies, namely soft-linking and hybrid models, are followed to link the two kinds of models.

Soft-linking of models is a practical strategy adapted to assess a given scenario on both top-down and bottom-up models. Figure 3 gives a stylized sketch of a soft-linked modelling system. The macro-economic consistency between the models is ensured by making the key drivers of the scenario (e.g. GDP, population) comparable. The relevant output from the run of one model is used to modify the information inputs for the other model. For example, the GDP loss resulting from a carbon tax regime which is assessed endogenously by the top-down model can then be used to alter the exogenous GDP inputs or the end-use demands provided as the input to the bottom-up model (Shukla et. al., 2008). The altered results of bottom-up model, e.g. technology shares, are then passed to the top-down model. The iterations are done by passing of information exogenously and sequentially across the models.

Thus, while the mathematical architectures of the models are not hard-linked, the models are soft-linked through information exchange. A short-coming of this approach is that it does not ensure theoretical consistency and full convergence of the results of both the models. Its key advantage is the simplicity of using models which follow two different paradigms and thereby receive deeper policy insights with less complexity of modelling.

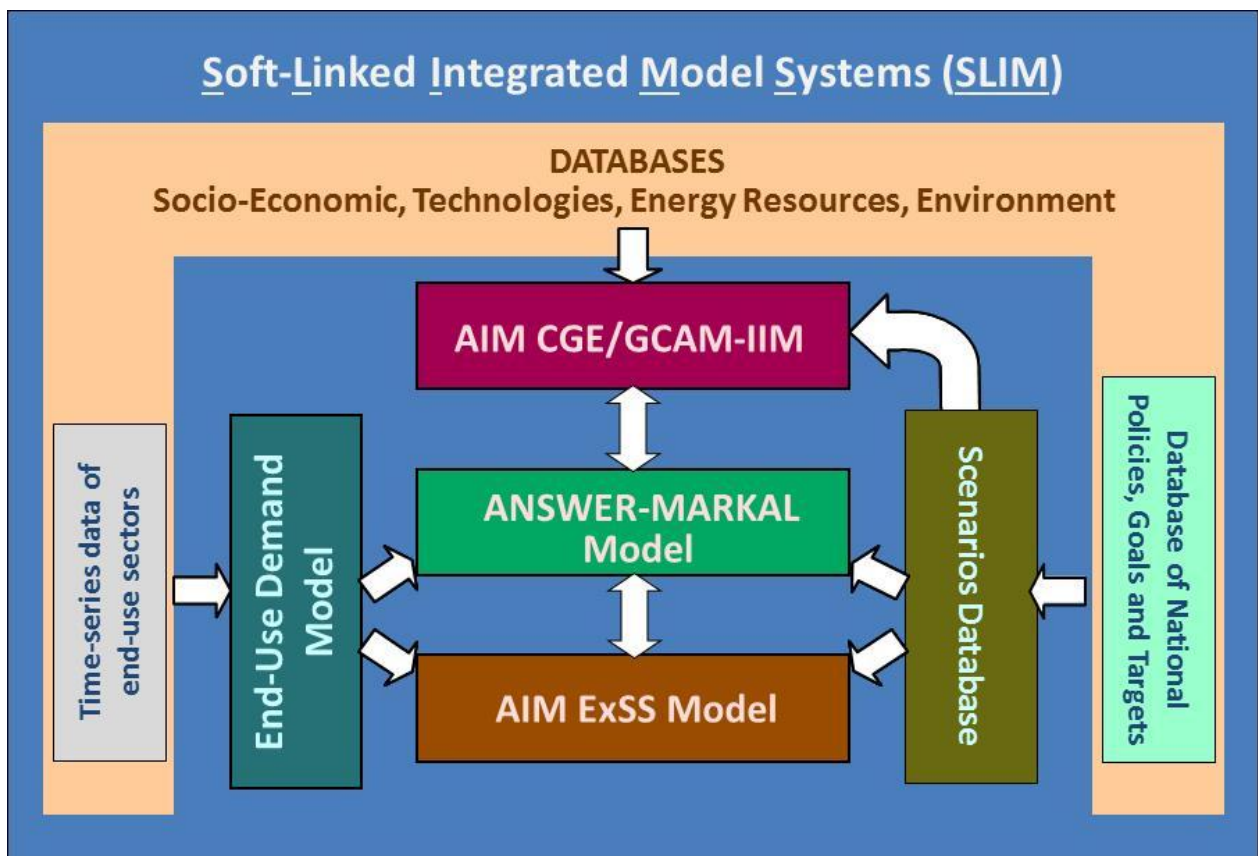


Figure 3: Soft-linked Framework for integrating AIM CGE and GCAM-IIM top-down models with a bottom-up model ANSWER-MARKAL

Hybrid models bridge the gap between the top-down and bottom-up models either by incorporating macroeconomic feedback in the bottom-up models or by including technological details in the top-down models (Carraro et.al.2012; Schafer et.al.2006; Kim & Edmonds 2006). The WITCH model (Bossetti et.al, 2006) allows improved representation of

energy sector details into the Ramsey-Cass- Koopmans optimal growth model. The MARKAL-MACRO model links bottom-up technology rich MARKAL model with inter-temporal general equilibrium MACRO model. The two models are solved simultaneously using non-linear optimization techniques (Loulou, 2004). The major challenges faced by hybrid models are theoretical consistency, computational complexity and policy relevance (Hourcade, 2006).

3.4. Integrated Assessment (Economic and Scientific) Models

An important limitation of energy models is that although they can estimate the lowest costs for mitigation, either based on energy system costs or the social welfare, they suffer from two major shortcomings:

- i) they ignore the contribution of other human activities in sectors like agriculture, forestry and waste towards GHG emissions; and
- ii) they do not provide any information about the impacts of human activities on ecosystems and human beings.

The Integrated Assessment Modelling framework came into vogue (Dowlatabadi, 1995) to address these concerns. Figure 4 provides a simple graphical representation of a typical IAM.

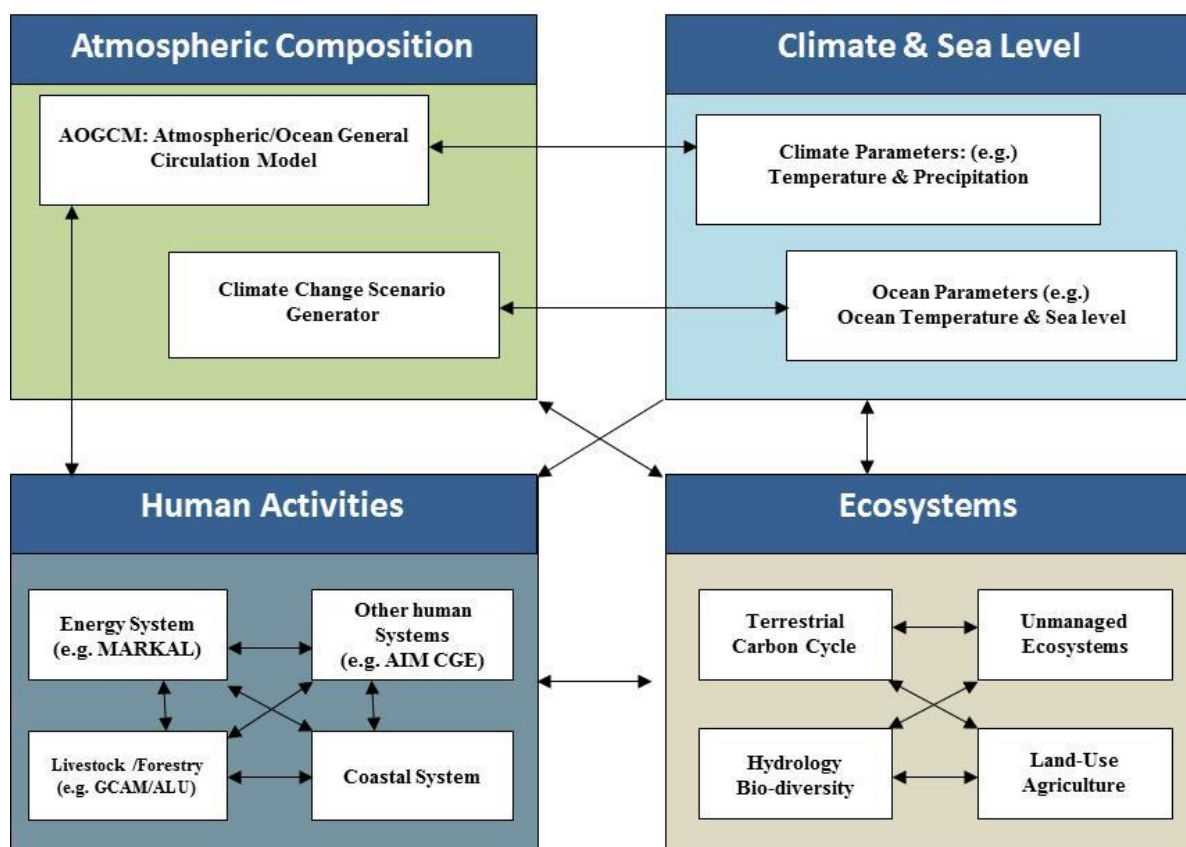


Figure 4: A Typical Integrated Assessment Model Framework

The IAMs normally comprise of four modules:

- i) a module to evaluate the greenhouse gas emissions from human activities,
- ii) a module to assess implication of GHG emissions on atmospheric concentration of GHG emissions,
- iii) a module to measure the implication of GHG concentrations on global temperatures and sea level, and
- iv) finally an ecosystems module which assesses the impacts of these changes on natural and managed ecosystems.

IAMs, thus, carryout socio-economic and scientific assessment of climate change by linking models from multiple disciplines (e.g. physics, atmospheric chemistry, ecology, engineering, economics etc.). The IAMs are used to assess the impact of constructed policies and measures on climate parameters, economics and ecological systems. IAMs are also used to delineate optimal policy at different spatial, temporal and sectoral scales to achieve desired climate goals; e.g. 2^oC stabilization target (Carraro et. al, 2012 ; Bosetti et. al, 2012; Calvin et al,2009; Shukla and Chaturvedi, 2012; Luken et. al, 2011;Neill et. al, 2012).

4. MODELLING ASSESSMENTS: TOOLS, DATA AND PURPOSE

4.1. Purpose of the Modelling Assessment

The purpose of the modelling assessment is to provide policy relevant information, based on the best available scientific knowledge and tools, to assist informed policymaking. The modelling for assessing low carbon development policies aims to answer a number of questions like:

- (ix) What is the resilience of natural systems to the climate tipping points?
- (x) How do population and consumption trends shape natural and societal interactions?
- (xi) What are the incentives and institutional structures - markets, rules, norms, taxes, quotas etc. - that transform societal interactions with nature to a sustainable path? and,
- (xii) How can research, planning, observation, analysis and decision support be better integrated (Swart et. al., 2004) with scenarios analysis?

Scenarios are the key constructs for articulating future dynamics. They permit analysis of situations characterized by high level of uncertainty, complexity and multiple objectives. Scenarios analysis 'project' trends in alternate futures; this is different to the conventional assessment constructs which aim to 'predict' the future. The IPCC Assessment Reports are a good example of how global climate change scenario modelling and policy assessments are carried out by the global scientific community for presenting the key findings to the policymakers across countries so as to assist them to delineate and align their actions towards common development and climate goals.

4.2. Soft and Hard Linking of Economic Models

Several researchers have attempted to develop hybrid economic models by linking bottom-up and top-down models to overcome the inherent weakness of these models. These efforts can be classified by four approaches (Bohringer and Rutherford, 2008):

- (i) Bottom-up and top-down models are soft-linked by passing information across models through the mediation by the modeler. The models are run separately and the soft-linking is continued until model results reasonably converge (Shukla et.al, 2008; Van den Broek et.al, 2011; Shukla et.al, 2010). E.g., this approach is used to represent U.S transport sector (Scafer and Jacoby, 2006) by linking "top-down" EPPA model and "bottom-up" MARKAL model.
- (ii) Bottom-up and top-down models are hard-linked through shared program code. Hard-linking focuses on one model type in detail and uses the "reduced" representation of the other. Some technology detailed bottom-up models are linked with a simple macroeconomic growth model; e.g. MARKAL- MACRO model wherein a technology detailed MARKAL model is integrated with neoclassical macroeconomic growth model MACRO using an economy-wide single production function. (Chen, 2005; Ko et.al, 2010).
- (iii) Technology details are represented into the top-down CGE (Wing, 2008; Eskeland, 2012) or partial equilibrium models (Clerk et. al, 2008).

- (iv) Both type of models are completely integrated within same optimization framework using the mixed complementarily problem solving routines applied to reduced-size models (Bohringer and Rutherford, 2008; Saveyn et.al, 2012, Lanz and Rausch, 2011, Proenca and Aubyn, 2013).

4.3. Strategic Databases (Socio-economic, Technical and Scientific Data)

Climate change modelling assessments require huge data inputs from wide ranging scientific disciplines at different spatial, temporal and sectoral scales. The commonly used databases, to name a few, include input-output tables, resource mapping data, economic and demographic growth trends, end-use sector production levels, technical parameters like efficiency and capacity of various technologies and database of climate parameters. Strategic global modelling databases like GTAP and AIM and generic global databases such as in the publications from IEA, OCED, UN and World Bank are typically used to maintain consistency across various models which can be soft-linked for comprehensive and integrated policy assessment. The national level modelling assessments use national databases from government sources as well as from other research institutions. Figure 5 shows a stylized strategic model database framework.

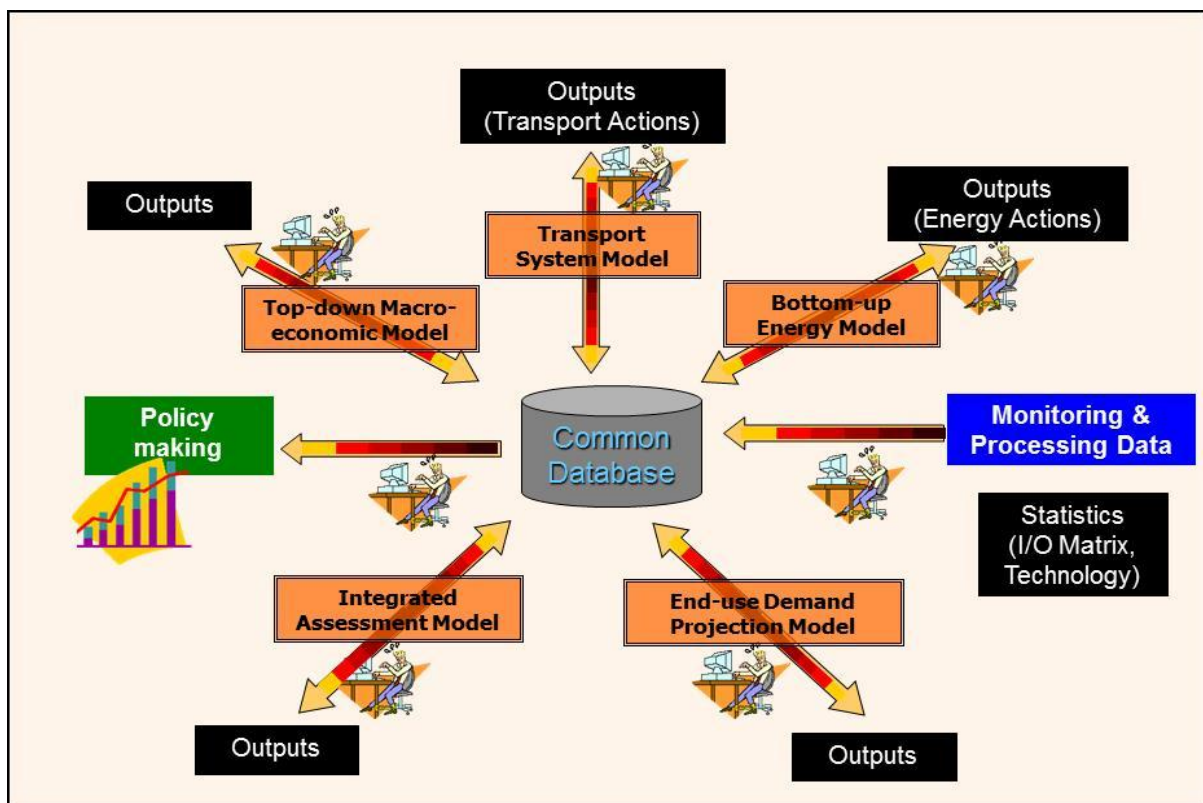


Figure 5: Strategic Model Database

4.4 Back-casting Framework to Align Development and Climate Goals

The co-benefits from aligning actions for climate change and sustainable development were formally recognised in the “Delhi Declaration” of the COP8 in 2002. It has long been argued that exclusive climate-centric actions tend to be very expensive. While significant opportunities for co-benefits exist, especially in developing countries, these have to be netted through policies and programs that align development and climate agenda. Sustainable development has been seen as an eminent framework for aligning development policies on a climate friendly track (Halsanæs and Shukla, 2007).

Back-casting (Figure 6) is the preferred modelling approach for assessment aiming to align national development goals with global climate targets like CO₂ stabilization. Back-casting is a normative approach where modellers construct desirable futures and specify upfront targets and then find out possible pathways to attain these targets (IPCC, 2001). In back-casting, the long-term national development objectives remain the key benchmarks guiding the model dynamics and the global climate goal is interfaced to realize the co-benefits. The model then delineates the roadmap of national actions that achieve the national goals and deliver optimal full costs and benefits of low carbon development including the costs of adaptation and impacts from residual climate change.

Back-casting modelling exercises show that aligning development and climate actions result in much lower ‘social cost of carbon’ (Shukla et. al., 2008). The back-casting does not aim to produce blueprints. It indicates the relative feasibility and the social, environmental, and political implications of different development and climate futures on the assumption of a clear relationship between goal setting and policy planning (Dreborg, 1996). Back-casting exercises are well suited for preparing local specific roadmaps like for the cities (Gomiet. al., 2010, Gomi et. al., 2011).

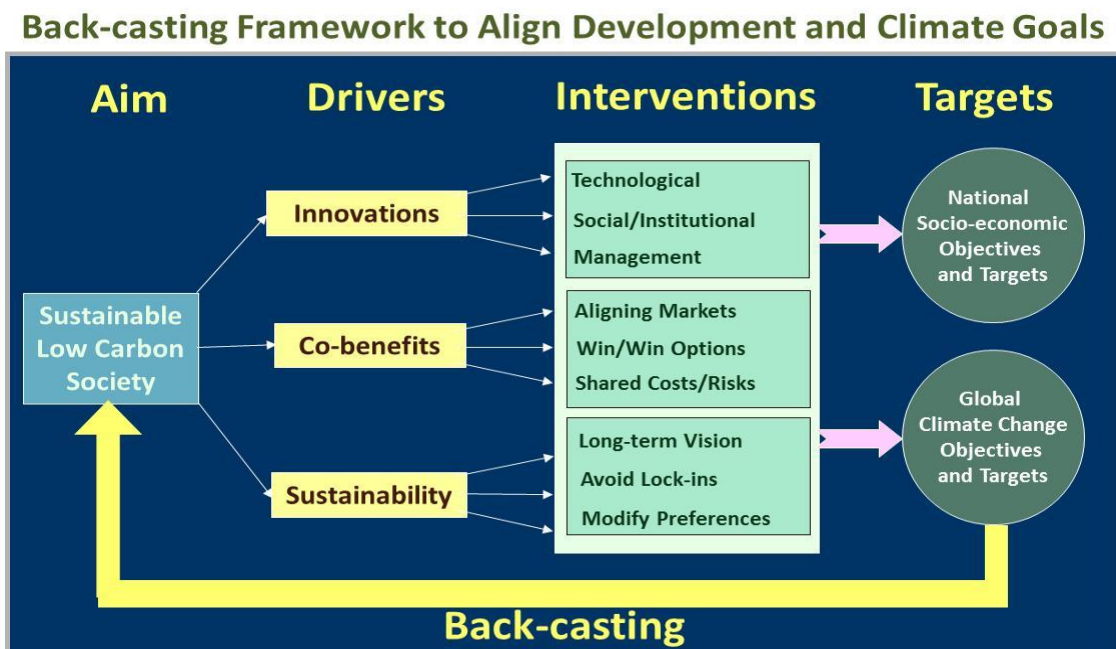


Figure 6: A backcasting framework to align development and climate goals

4.5. Scenarios

Scenarios are plausible representations of how the future may develop, based on a coherent and inherently consistent set of assumptions about driving forces and key relationships (IPCC, 2007). Scenarios are classified in three categories: predictive, explorative and normative. The predictive scenarios are constructed to predict or forecast the future trends (Borjeson et.al, 2006) over the short to medium term. Explorative scenarios try to explore the development that can possibly happen in future (Soderholm et.al, 2011). They facilitate the assessment of the impacts of various policy interventions, like carbon tax or energy efficiency regulation, relative to a reference or “non-intervention” scenario.

The Special Report on Emissions Scenarios (SRES) (IPCC, 2000) is an example of exploratory scenarios which assume different development pathways depending upon the degree of globalization versus regionalization and economic growth

versus environmental protection. Normative (or perspective) scenarios describe the preferable future state. These scenarios are used to assess the feasibility of desired futures. Low carbon scenarios having specific emission reduction targets are examples of normative scenarios (Gomi et.al, 2010; Dagoumas& Barker, 2010; Ashina et.al, 2012; Fujinoet.al.,2008). Explorative and normative scenarios are adopted for long term studies and therefore help to avoid lock-ins that can happen due to short-sightedness of the decision maker.

4.6. Choice of Parameters

The choice of parameters is generally driven by the research focus and objective. For example if the objective is to study the transportation sector, the parameters driving the energy demand would be population, income, urbanization, city structure, type of industrialization etc. While if the objective is to study the building energy demand, the parameters like number of households, household income, surface area of buildings, etc. would be the driving factors.

When the research objective is to find impacts of macroeconomic policies, e.g. carbon tax, then the behavioural parameters like elasticity of substitution of consumption goods or the technical parameter like elasticity of substitution of inputs would be relevant. If research is to assess technology policies, such as incentives for R&D, then the technological parameters related to endogenous learning would be pertinent. The choice of parameters gives flexibility to choose relevant combinations of research objectives and models.

The typical objectives for low carbon development and mitigation modelling include achieving low carbon emissions target (such as 2°C stabilization) at minimum cost including and maximum net co-benefits while meeting the real-life constraints. In case of national level low carbon development modelling, the carbon price trajectory to achieve 2°C stabilization can be a key exogenous parameter. This is generally obtained from the 2°C stabilization scenario results of global integrated assessment models. The national exercise can use the carbon price as a tax on the national system. Here, the choice of parameters would also include the key indicators selected for assessing co-benefits with a view to align national development and climate objectives.

For sectoral models, the objective often is to assess the implications of low carbon development on the competitiveness of the sector outputs. The exogenous parameter choices then would include technology cost structures, supply curves resources, carbon price expectations and demand for sector outputs. In case of locale of specific models, e.g. low carbon city development models, the parameters such as floor space use, trip lengths and structure of industry would be appropriate, in addition to generic technology and resource related information which may be derived from national and/or global models.

In general, while the choice of parameters depends primarily on objectives, some parameter choices also depend on the real-life constraints as well as the type of model being used.

5. REVIEW OF LOW CARBON DEVELOPMENT MODELLING STUDIES

The review of low carbon development studies show a great deal of heterogeneity in terms of:

- (v) use of models,
- (vi) scenarios assumptions,
- (vii) policy objectives,
- (viii) choice of socio-economic, resources and technology parameters, and
- (ix) modelling approaches.

Sectoral models are used in key GHG emitting sectors like electricity, energy intensive industries, agriculture, forestry and land-use. In some cases, sectoral models are linked to an economy-wide model so as to receive the feedback from aggregate economy-wide signals which may alter competitive dynamics of the sector or provide key insights into the sector specific mitigation measures.

Several modelling studies in the developing countries follow a 'low carbon society' approach. These studies use soft-linked models which connect and align the global stabilization targets to national and local dynamics, objectives and constraints along the geographical hierarchy linking the global to the local scale.

The scenarios data and model related parameters can be shared among models sharing a similar paradigm and scope of the assessment. However, the heterogeneity of the models, modelling approaches and scenario specifications create a huge demand for diverse data. The heterogeneity results in low comparability of modelling results across studies. Global modelling community has moderately succeeded in overcoming these lacunae by sharing common modelling protocol across studies undertaken by different modelling teams (Calvin et. al, 2012).

5.1. Studies linking top-down and bottom-up approaches

There are few studies which link top-down models with bottom-up models. For example Okagawa et al. (2012) use a top-down AIM/CGE model and link it with bottom-up AIM/ENDUSE model while assessing GHG emission pathways for Japan, China, and India. In another study by Gambhir et al. (2013), a top-down MESSAGE model is soft linked with a bottom-up model by the Grantham Institute to develop scenarios for China's CO₂ emissions up to 2050. Shukla et al. (2010) use a top-down AIM/CGE model and soft link it with bottom-up ANSWER-MARKAL model to assess alternate development pathways for India. The first pathway assumes a conventional development pattern together with carbon price, while the second emission pathway assumes an underlying sustainable development pattern.

5.2. Studies linking sectoral and economy-wide models

The key reason for linking a sectoral model with economy-wide model is to receive the feedback from the aggregate economy-wide signals. Many studies use a sectoral model (e.g. land use or transport or electricity sector) and link with the economy-wide models. These models focus on a particular sector and help modelling of sector specific issues, dynamics

and policies in detail. For example, Shukla et al. (2010) have used a land-use model along with an integrated assessment model using AIM/CGE model and ANSWER-MARKAL.

The Land-use Model analyzes land demand for the deployment of renewable energy sources (biomass, biofuel plantations, solar) and is soft linked with the ANSWER-MARKAL model. In another study by Hu et al. (2011), the authors have used E-4 framework (Economy-Energy-Electricity-Environment) which includes electricity and energy sector models which are linked to an economy and emissions model. The electricity sector model, for instance, projects electricity supply and demand using feedback from the economy-wide model.

5.3. Low carbon society modelling studies

Countries differ in energy resource endowments, geographical conditions, state of economic development and national priorities. A key issue for modelling studies is how to bridge the gap between the abstract world dynamics in the models with the real world dynamics wherein the policies are framed at specific times and in specific locales. A first step to bridge this gap is to translate aggregate modelling results into disaggregated, temporally and geographically downscaled, detailed and implementable roadmaps. The low carbon society (LCS) modelling studies (Kainuma et. al., 2012) are an example of how this can be achieved..

LCS modelling exercises, offer promise in a world where developing economies are expected to undergo rapid transformation during the coming decades. This transformation period poses dual challenges. First, the national and regional interests shall drive the core national development policies. Secondly, the low carbon development shall require aligning national development interests with global climate change targets. This duality shall pose risks to *in situ* national development goals as well as opportunities for gaining co-benefits of the low carbon transition. The LCS modelling soft-links global stabilization targets through appropriate regional emission constraints. The disaggregated, yet soft-linked, assessments provide opportunities to articulate scenarios that include context-specific inputs, and thereby explicitly consider benefits and deliver realistic and implementable roadmaps.

LCS modelling approaches from several countries in Asia, namely China (Jiang et. al.; 2008; Jiang et. al., 2012), India (Shukla, 2006; Shukla et. al. 2008, Shukla et. al., 2009, Shukla and Chaturvedi, 2011; Shukla and Chaturvedi 2012), Japan (2050_Japan_LCS_Team, 2009; Kainuma, 2009), Korea (Kainuma et. al, 2012) and Nepal (Shrestha and Shakya, 2012) explicitly include policies which aim at low-carbon energy supply, 3R (Reduce, Reuse, Recycle), dematerialization and low-carbon infrastructure. Deploying these options requires a combination of taxes, subsidies, and technology transfer, with the specific choice of policy instrument varying by country and option.

The LCS modelling approach is still in its early stages of development and needs methodological enhancements. However, the approach offers considerable promise over the next decades.. Their national and regional aspirations and interests hence are expected to precede global interests, but simultaneously universal solutions shall be needed to address efficient low carbon development and mitigation regimes.

LCS modelling studies cover different time horizons; long-term (e.g. 100 years; Shukla and Chaturvedi, 2012), medium term (e.g. 20-40 years; Ashina et al., 2012) and short term (e.g. 10-20 years; Hu et al., 2011). Bottom-up models are used for short to medium time horizon studies; whereas top-down and integrated assessment models are used for medium to long term time horizon studies. For short to medium term, a few low carbon society studies use econometric type assessment

based on current and past data to draw inferences (Liu et al., 2013; Huang & Barker, 2012). Whereas the LCS studies mentioned earlier focus on thenational scale, a few global (Carrarro et al., 2012) and regional (Saveyen et al., 2012) studies also exist. There is sizable literature on LCS modelling studies at the city scale (NIES/AIM website, 2013; Phdungsilp, 2010).

5.4. Information on socio-economic, resources and technology parameters

All low carbon modelling studies use a combination of various socio economic parameters. The choice of parameters depends on the research objective of the study. The common parameters used in these studies are related to GDP, demographics, technologies, reserves of conventional resources and potentials of renewable resources. These parameters are provided as exogenous data to a model. The type of input parameters needed for setting up a model exercise may also vary depending on the scenario to be assessed. The output parameters depend on the objectives of the modelling exercise.

For example a study aiming to assess the long-term household energy demand would need data related to socio-economic and physical parameters for each income class, such as: per capita income, growth rate of income, household-size, floor space per household, expected technology improvements and income elasticity of consumption (Chaturvedi et. al., 2012). Similarly, a study aiming to assess low carbon transport plan for a city would need to develop a dataset including parameters such as population, number of trips per person, trip length, share of mobility across different transport modes, mix of vehicles, fuel efficiency standards of vehicle stock, vehicle environmental standards such as 'Euro Standards', fuel-mix standards (e.g. percentage of ethanol mix in gasoline), carbon content of electricity supplied to the city and emissions co-efficient of vehicle and fuel combination. The parameters database would be unique to each scenario.

A reasonable fraction of exogenous parameter data is available from publicly available sources like reports of the national government, international agencies like UN, IEA, World Bank. Scientific data, such as emissions co-efficient of fuels, is available from generic global sources like IPCC (IPCC, 2006) and also 'National Communications' inventory databases at country level. The key issue in parameter choice for national modelling exercises is the consistency of the scenario assumptions with the information obtained from the global exercises.

The data needs for the low carbon development modelling studies are enormous due to global, long-term and socio-economically pervasive nature of the climate change issue. The SRES framework which is typically used for the policy assessments is data intensive due to the need to asses numerous scenarios (i.e. plausible futures) to delineate robust conclusions (SRES, 2000; IPCC WGIII, 2007). The extent of the data needs varies depending on the scenario dimensions such as the time-horizon, space and sector coverage. Figure 4 gives an illustrative list of parameters contained in scenario databases.

TABLE 4: TYPICAL PARAMETERS FOR KEY SCENARIO DIMENSIONS (ILLUSTRATIVE LIST)

PARAMETER SPACE	TEMPORAL (SHORT, MEDIUM, LONG-TERM)	REGIONAL (GLOBAL, NATIONAL, SUB-NATIONAL)	SECTORAL (KEY SECTORS: ENERGY, INDUSTRY, TRANSPORT, BUILDINGS, AFOLU, WASTE)
GDP / Income	<u>Time trends of factors:</u> i) Labor supply ii) Land supply iii) Savings/Investment iv) Productivity v) Trade	<u>Region specific:</u> i) Labor Supply ii) Land Supply iii) Savings/Investment iv) Productivity v) Trade vi) Resource endowments	<u>Sector specific:</u> i) Demand ii) Supply iii) Infrastructure iv) Skills/ R&D capacity v) Investment vi) Comparative advantage (for production sectors)
Demographics	<u>Time trends of:</u> i) Population ii) Gender/Age Profile iii) Urbanization iv) Education v) Life expectancy vi) Gini Co-efficient vii) Migration	<u>Region specific:</u> i) Population ii) Gender/Age Profile iii) Urbanization iv) Education v) Life expectancy vi) Gini Co-efficient vii) Net Immigration	<u>Sector specific:</u> i) Labor supply ii) Education/Skills iii) % Migrant workers iv) Wages v) Consumption of sector output
Technological Change	<u>Time trends of:</u> i) Technological Learning ii) R&D Investments iii) Technology trade iv) Technology trade across regions	<u>Region Specific:</u> i) Technological Learning ii) R&D Investments iii) Technology trade iv) Technology transfer in and out of region	<u>Sector specific:</u> i) Technological learning ii) R&D Investments iii) Technology trade iv) Technology transfer in and out of region
Resources (e.g. energy)	<u>Time trends of resource:</u> i) Reserves ii) Production iii) Trade iv) Price	<u>Region specific resource:</u> i) Reserve ii) Annual Production iii) Trade iv) Price	<u>Sector specific resource:</u> i) Demand ii) Use efficiency iii) Trade iv) Elasticity of substitution
Carbon mitigation related parameters for agreed climate target (e.g. <20C Stabilization)	<u>Time trends of:</u> i) Emissions co-efficient ii) Global Carbon Budget Pathway iii) Limitations on global carbon off-sets trade iv) Co-benefits metric - energy access, energy security poverty, food security, air quality, water stress etc.	<u>Region specific:</u> i) Emissions co-efficient ii) Regional Carbon Budget Pathway iii) Carbon Price Pathway v) Limitations on regional carbon off-sets trade iv) Co-benefits metric - energy access, energy security poverty, food security, air quality, water stress etc.	<u>Sector specific:</u> i) Emissions co-efficient ii) Carbon Budget Pathway for a sector iii) Carbon Price Pathway iv) Limitations on sectoral carbon off-sets trade v) Co-benefits metric - energy access, energy security poverty, food security, air quality, water stress etc.

The sources of information about some of the key parameters used in modelling exercises depend on the type of the model used. A dichotomy typically used to classify the source of modelling parameters uses the labels endogenous versus exogenous. Endogenous values of parameters are generated internally by a modelling study. The exogenous values of parameters are supplied to the model as a part of dataset of a modelling exercise. Table 5 shows the source of information about socio-economic, technological or resources related parameter. Often, endogenously generated parameter information from one model is used as an exogenous input in another model.

Top-down models deliver several key socio-economic parameters endogenously whereas bottom-up models rely more on the exogenous information (Table 5). An example is the future GDP projection which is an endogenous output of a top-down macro-economic model and is often supplied to a bottom-up model as exogenous data, especially in modelling exercises that align the top-down and bottom-up assessments. For accounting type, bottom-up models (Gomi, 2008), most information about the key parameters is exogenous. In hybrid models, which cross-link top-down and bottom-up models, the endogenously generated parameters from top-down models are passed to bottom-up models during the model iterations.

TABLE 5: SOURCES OF KEY PARAMETERS FOR DIFFERENT MODEL PARADIGMS (ILLUSTRATIVE LIST)

PARAMETER SPACE	TOP-DOWN	BOTTOM-UP
GDP / Income	<ul style="list-style-type: none"> • Endogenous; based on productivity, savings, consumption elasticity etc. 	<ul style="list-style-type: none"> • Exogenous; provided as a part of scenario dataset
Demographics	<ul style="list-style-type: none"> • Mostly Exogenous • Influence of macro-economic parameters on demographic parameters, e.g. income on fertility, can be endogenously assessed 	<ul style="list-style-type: none"> • Exogenous; provided as a part of scenario dataset
Technological Change	<ul style="list-style-type: none"> • Endogenous learning in few studies • Exogenous in most studies 	<ul style="list-style-type: none"> • Exogenous time path of declining costs
Resource (e.g. energy) and Technology Prices	<ul style="list-style-type: none"> • Endogenous in most global models with regional trade • Exogenous for global resources in national modelling studies 	<ul style="list-style-type: none"> • Time path of prices and technology parameters is provided exogenously
Carbon Price for agreed climate target (e.g. <math>2^{\circ}\text{C}</math> Stabilization)	<ul style="list-style-type: none"> • Endogenous carbon price trajectory in integrated assessment modelling studies assuming global emissions trading • Exogenous in national modelling studies 	<ul style="list-style-type: none"> • Exogenous, in general • ‘<i>Social value of carbon</i>’ can be assessed endogenously in the national level studies including carbon budget and co-benefits

5.5. Comparative Assessment of Modelling Approaches in MAPS and CDKN Linking Project

Five modelling teams from COPPE Brazil³, EC Chile⁴, UniAndes Colombia⁵, IIAP Peru⁶ and ERC South Africa⁷ are working as partners on a CDKN⁸ funded project 'Modelling the implications of socio-economic development of mitigation actions by developing countries'. The modelling teams are working to develop sophisticated models needed to answer policy relevant questions on the implications of mitigation action within their respective countries. These five institutions are also part of the broader Mitigation Action Plans and Scenarios (MAPS) project. MAPS, a collaboration amongst developing countries, which aims to establish the evidence base for long term transition to robust economies that are carbon efficient.

The linking project was initiated taking cognizance of the following: firstly, the policy makers needed reliable information on the socio-economic impacts of various mitigation options; secondly, the modelling required to elicit this information was not adequately available in the target countries; and thirdly, the socio-economic information generated from the project would assist decision makers within MAPS to craft ambitious climate change mitigation policies.

An evident feature of the MAPS modelling exercises is the diversity of models, used by the country teams. The two key reasons for the choice of a model by a country team are: first, the specificity of national policy agenda which can be addressed only by certain class of models; and second, is the familiarity and capacity of a national modelling team vis-à-vis use of specific models. A key issue is also the availability of the data to support the modelling assessment.

The next provides a brief description of models used in MAPS and CDKN linking project. Table 6 summarizes the model features and applications in MAPS and CDKN linking project.

5.5.1 Brief Description of Models used in MAPS and CDKN Linking Project

1. **IMACLIM-S:** IMACLIM-S is a general equilibrium hybrid model developed adapting the version built by CIREN⁹, France (Crassous et al, 2006; Gherzi and Hourcade, 2006). The model combines top-down and bottom-up approaches using a double accounting system and both physical and economic flows are equilibrated in the model. It is designed to assess the medium and long-term macroeconomic impact of climate change policies like carbon constraint. (Wills et.al, 2013)
2. **MESSAGE:** The MESSAGE model was developed by IIASA¹⁰, Austria. MESSAGE is a partial equilibrium optimization model having detailed technical and economic details of various technologies that helps to arrive at the optimal energy mix using the least cost minimization criterion over the given time horizon (Hainoun et al., 2010). It represents the reference energy system which describes the complete energy system flow from primary energy sources to end-use energy sector using various conversion technologies (Lucena et.al, 2010; La Rovere et. al., 2013).

³ COPPE refers to: Environmental Sciences Laboratory and Center for Integrated Studies on Climate Change and the Environment at the Institute for Research and Postgraduate Studies in Engineering of Federal University of Rio de Janeiro

⁴ Energy Centre, University of Chile

⁵ UniAndes refers to the Energy Strategic Research Centre, Universidad De los Andes

⁶ Instituto de Investigación de la Amazonía Peruana, (Peruvian Amazon Research Institute)

⁷ Energy Research Centre, University of Cape Town

⁸ CDKN: The Climate and Development Knowledge Network

⁹ Centre International de Recherche sur l'Environnement et le Développement

¹⁰ International Institute for Applied Systems Analysis

3. **LEAP:** LEAP is an accounting model developed at SEI¹¹ for medium and long term energy planning and scenario analysis at local, national and regional level (Park et.al.2013). It doesn't give optimal solution or simulate the response of customer and producers but it explores the environment and economic cost implications of various energy scenarios. It is simple and flexible and has lower data requirements. Hence it is therefore beneficial for the developing countries where data is very sparse.
4. **BLUM:** BLUM is a one-country, multi-regional, multi-market and partial equilibrium model used to study the dynamics of Brazilian agricultural sector (Nassaret.al, 2010). The model comprises information regarding supply and demand and land allocation in 6 macro regions of Brazil. Based on the land allocation, the supply of the agricultural products is estimated. It helps to assess the impacts of land-use change due to sudden demand shock like increasing demand of bio-fuels in Brazil (Nassaret.al, 2010).
5. **DSGE:** The version of DSGE (Dynamic stochastic general equilibrium model) used in MAPS project is developed by the Central Bank of Chile and is called Chilean Ministry of Finance's DSGE model. It is designed to assess how the economy would evolve over time (dynamic) and takes into account effect of random shocks such as oil price fluctuations, macroeconomic policy making changes, technological changes, etc (stochastic) on the economy on a medium term horizon. Preferences, productive capacity of agents and the institutional constraints are specified to run the model. The model would be linked with the Chilean Energy Centre's Electricity Planning model and would be used to analyze the economic impact of various mitigation options such as carbon tax/cap and trade scheme on Chile's electricity sector (Medina and Soto, 2006).
6. **Electricity Planning Model:** The inputs from the Electricity Planning model developed by the Energy Centre, University of Chile are used as input for the DSGE model which analyze the economic impact of various mitigation options (for e.g. carbon tax) on Chile's electricity sector (ERC, 2013a).The objective function minimizes sum of capital costs, operation costs, the cost of unsaved energy plus a carbon e.g. carbon tax. MATHPROG and the GLPK solver are used to find the solution to the optimization problem. The model is also used to delineate the optimal mix of power generation to meet the projected electricity demand and the estimates the cost of electricity.
7. **DNP CGE Model:** It is a simulation model developed by the Department of National Planning (DNP), Colombia and is called the DNP CGE model (Rincon, 2010).The simulations are calibrated on GAMS platform with MCP solver, which applies a mixed complementarity algorithm to reach the solution. The algorithm uses the general method of nonlinear programming to structure the model. The model is used to estimate the impact of sectoral tariff variations on the economy.
8. **MARKAL:** MARKAL (MARKet ALlocation) model is an inter-temporal partial equilibrium bottom-up model based on linear programming optimization technique to minimize the total system's energy cost (Loulou, 2004). This is high disaggregated model with detail specification about the existing and future end-use and conversion technologies, used for medium to long term energy planning and energy policy analysis at national and global level. The model relies on the basic assumption that we have perfect foresight about the changing technologies and economic situations.
9. **SATIM:** The South African TIMES energy model (SATIM: ERC; 2013b) is a national level partial equilibrium least-cost optimization model developed by the Energy Research Centre (ERC), University of Cape Town. The methodology factors-in the detailed specifications of various technological options subject to various emissions, sectoral, and economic constraints and make projections for build plan and related investment costs, electricity prices etc..

¹¹Stockholm Environment Institute

10. **E-SAGE Model:** The South African Computable General equilibrium (E-SAGE: ERC; 2013b) is a top-down economy wide model. In the CDKN project, ESAGE and SATIM are linked to gain advantages of both the models. E-SAGE is used for projecting sectoral energy demand, fossil fuel prices and the electricity generation plan. E-SAGE output is an input into SATIM which makes techno-economic plans and finds investment costs and electricity prices which are provided as inputs to ESAGE model. The two models are soft-linked and are runs iteratively.

TABLE 6: SUMMARY OF MODEL APPLICATIONS IN MAPS AND CDKN LINKING PROJECT

SR. NO.	COUNTRY	MODELLING INSTITUTION	MODEL NAME	MODEL SUMMARY	APPLICATION	REFERENCES
1	Brazil	CIRED	IMACLIM-S	IMACLIM-S is a general equilibrium hybrid model designed to assess the macroeconomic impact of climate change policies like carbon constraint. Both physical and economic flows are equilibrated.	Impact of carbon price on Brazilian economy	Wills et.al.(2013); La Rovere et. al. (2013)
2	Brazil	IIASA	MESSAGE	Partial equilibrium, bottom-up model Based on Least cost optimization framework	Assessing medium and long term impact of plug-in hybrid electric vehicles (PHEV) on integration of wind energy in Brazilian power system and to delineate least cost adaptation measures for climatic impact on Brazilian power sector.	Borba et.al.(2012) ; Lucena et.al.(2010)
3	Brazil	Stockholm Environment Institute	LEAP	Accounting model suitable for developing countries where data is sparse. Used for medium and long term planning	Assessment of energy demand in transport, industry, household and service sectors	Park et al. (2013)
4	Brazil	ICONE's research team	BLUM	BLUM is a one-country, multi-regional, multi-market, dynamic, partial equilibrium for Brazilian agricultural sector	Assessing the impact of land-use change, simulate supply and demand of agricultural products produced in Brazil	Nassar et.al.(2010)
5	Chile	Central Bank of Chile	DSGE	- General equilibrium model used for medium term horizon - Model assesses how economy evolves over time (dynamic) and takes into account effect of random shocks such as oil price fluctuations, macroeconomic policy making changes, etc (stochastic) on the economy	Economic impact of various mitigation option like carbon tax/ cap and trade scheme on Chile's electricity sector	Medina& Soto (2006)
6	Chile	Energy Centre	Electricity Planning model	- The objective function is to minimize the capital costs in new plants, the operation costs and the cost of unsaved energy and includes a penalty based on carbon tax - MATHPROG and the GLPK solver is used to find the solution to the optimization problem	- Projection of an optimal mix of power generation to meet the projected electricity demand - Projection of cost of electricity	ERC(2013a)
7	Colombia	Department of National Planning	DNP CGE model	- Simulation model; The simulations are calibrated on GAMS platform with MCP solver, which applies a mixed complementarity algorithm to reach the solution - The algorithm uses the general method of nonlinear programming to structure the model	Impact of sectoral tariff variations on the Colombian economy	Rincón (2010)
8	Colombia	ETSAP	MARKAL	Partial Equilibrium, bottom-up, optimization model. It is highly disaggregated model with detailed representation of energy sector	implications for the economy of Colombia of Kyoto Protocol	Goldstein and Tosato (2008)
9	Peru	-	Linked Biometric& Econometric models	Framework for model is under discussion	- Estimation of GHG mitigation cost for agro-forestry system (AF) and Forest plantations (FP) - Feasibility of funding AF and FP with revenues from fossil fuels and public funds	ERC(2013a)
10	South Africa	ERC, University of Cape Town	E-Sage	Top-down Computable General Equilibrium Model	Projection of GDP and sectoral growth, house-hold income, sectoral energy demand, and committed build plan for electricity generation plant.	ERC(2013a)
11	South Africa	ERC, University of Cape Town	SATIM	Partial equilibrium optimization model used to assess the potential of various mitigation options	Projection of investment, electricity and liquid fuel prices subject to various emissions, sectoral, and economic constraints.	ERC (2013b)

6. CONCLUSIONS AND KEY MESSAGES

This paper reviewed the models and modelling applications aimed at low carbon development. The conclusions and key messages below follow from the literature on the state-of-the-art of models; variety of modelling studies, especially those focused on developing countries; and experiences of MAPS and CDKN linking project for modelling of low-carbon development, mitigation and assessment of its full costs and benefits.

- The purpose of a modelling assessment is to delineate low carbon development policies that address key questions raised by policymakers and other stakeholders using state-of-the-art scientific knowledge and modelling tools. The modelling assessments typically address multiple questions such as: How shall demographic trends, consumption behaviour, income effects and resource constraints influence greenhouse emissions? What incentives and institutional structures - markets, rules, norms, taxes, quotas etc. - can transform societal interactions with nature to follow a sustainable path? How can research, planning, observation, analysis and decision support be better integrated with scenarios analysis?
- Policy concerns vary depending on the spatial and temporal scales and sector specificities. Therefore the selection of a model and the modelling practice vary depending on the intent and the nature of policy issue to be addressed. The global climate change policymakers' have varied concerns; e.g. assigning historical responsibility; overcoming inherited lock-ins; agreement on long-term GHG concentration stabilization target; distribution of full costs of climate change mitigation and adaptation actions equitably among nations while following the 'precautionary principle' and ensuring 'intergenerational equity'.
- National policymakers have wide-ranging concerns vis-à-vis low carbon development. Typical of these are the implications of mitigation policies and measures on energy security, energy access, incremental job creation and poverty.
- The GHG mitigation problem links the local policy issues directly with the global socio-economic and environmental policy dynamics. For instance, in the local policy context, low carbon development generally has positive effects on air quality in cities. However, the increase in price of kerosene, a fuel used by the poor for cooking and lighting, could worsen the indoor air quality if traditional biomass replaces kerosene.
- The typology of models for the assessment of low carbon development is diverse and purposive. Model architectures and modelling approaches differ depending on the type of policy questions they address. Policy questions vary according to spatial, temporal and sectoral focus; the costs, benefits and risks included in the analysis; and the types of mitigation policies and measures being assessed.
- A policy model, besides being a purposive computational device used by the analysts, is essentially a communication tool that elucidates the information that enhances understanding among scientists, policymakers and other stakeholders.
- Model structures and computational methods rest on scientific and mathematical foundations. The choice of model rests on practical rationality, e.g. following the 'horses for courses' approach. Modelling is an art of fine-tuning and

focusing a selected model on the question being pursued to find the 'right answer'. Models are formal, transparent and verifiable tools of communication; the best-use choice is with the user.

- A bulk of GHG emissions emanate from the energy sector, hence, significant mitigation modelling efforts are focused on the energy system. Sizable modelling assessments are also devoted to other key GHG emitting sectors; e.g. agriculture, forestry and land-use changes. Energy models are differentiated on the basis of their economic rationale, disaggregation, temporal dynamics, geographic and sectoral coverage, aims and questions, degrees of endogenization and the underlying mathematical techniques.
- The aim of a modelling assessment is to assist policymakers using the best available knowledge and tools. The scenarios are used as the key constructs for articulating the future dynamics. Scenarios analysis 'projects' the trends in alternate futures; as opposed to the conventional assessments that aim to 'predict' or forecast the future. The policy assessments use two approaches; the conventional forecasting approach and the back-casting approach wherein the models aim to achieve multiple goals, including the climate goal, and thereby delineate the policies and measures that optimize full costs and benefits.
- Models are supported by strategic databases which contain enormous amounts of information; e.g. technology trends, resource constraints and demographic and economic trends. The modelling assessments are based on numerous assumptions about the drivers of alternate futures (scenarios) and a set of policy objectives or aims. The choice of modelling parameters depends primarily on objectives but also real-life constraints and the type of model being used.
- The review of low carbon development studies show a great deal of heterogeneity in terms of: i) use of models, ii) scenarios assumptions, iii) policy objectives, iv) choice of socio-economic, resources and technology parameters, and v) modelling approaches. There are a few studies which link top-down models with bottom-up models.
- Sectoral models are used in key GHG emitting sectors like electricity, energy intensive industries, agriculture, forestry and land-use. In some cases, sectoral models are linked to an economy-wide model so as to receive the feedback from aggregate economy-wide signals which may alter competitive dynamics of the sector or provide key insights into the sector specific mitigation measures.
- Several modelling studies in the developing countries follow a 'low carbon society' approach. These studies use soft-linked models which connect and align the global stabilization targets to national and local dynamics, objectives and constraints along the geographical hierarchy linking the global to the local scale.
- The scenarios data and model related parameters can be shared among models that follow similar paradigm and scope of the assessment. However, the heterogeneity of the models, modelling approaches and scenario specifications create a huge demand for diverse data and low comparability of modelling results across studies. Global modelling community has moderately succeeded in overcoming these lacunae by sharing common modelling protocols across studies undertaken by different modelling teams.
- An important cooperative modelling exercise for long term transition to robust and a carbon efficient economy is organized under the MAPS and CDKN Linking Project. Five modelling teams - COPPE Brazil, EC Chile, UniAndes

Colombia, IIAP Peru and ERC South Africa - are working as partners on the project. These five institutions are also part of the broader Mitigation Action Plans and Scenarios (MAPS) project.

- The comparative assessment of modelling approaches in the MAPS and CDKN Linking Project demonstrates the diversity of policy issues in developing countries that are posed to the modelling assessments; the variety of models and modelling approaches needed to address these issues; the need for modelling capacity building; and the value of shared databases and sharing of modelling experiences among the developing countries.
- Focus of most modelling applications in the MAPS and CDKN Linking Project is at the national level. The model applications however, are diverse, e.g. impact of global carbon price, impact of plug-in hybrid electric vehicles (PHEV), future cost of electricity supply, assessment of sectoral energy demand, impact of sectoral tariff variation on national economy, impact of land-use change on agriculture, cost of GHG mitigation for agro- forestry and forest plantations, estimation of future investment in energy sector.
- The diversity of models used by modelling teams arise since model choices depend on the policy questions posed and the familiarity and capacity of a national modelling team vis-à-vis use of specific models. The MAPS and CDKN Linking Project demonstrates the urgent need and immense value of capacity building for policy modelling in developing countries.

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