The Ecological Sequestration Trust Modeling Effort

Revision Date:	February 06, 2012
Revision:	V1.3
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1. Background

The Ecological Sequestration Trust will use new design concepts, integrated resource models and pilot projects to demonstrate and optimise new settlements with tightly closed resource loops. There are two main objectives to the early part of its work programme:

- Develop a generic set of closed loop development concepts, strongly supported by modelling;
- Demonstrate the approach in a number of ground-breaking pilot projects

As data is generated, a third activity might involve a "serious game" which will be available via the web for users to explore designs for their own settlements.

This document scopes out the work in integrated resource flow, technology and economic activities modelling.

IIER and Imperial College are committed to supporting the efforts of the Sequestration Trust by providing input into the required models for economic systems which employ a "short carbon cycle". Ideally, this concept is represented by a city, supply hinterland, and the outside world, operating in a sustainable way by cycling all key inputs so the city plus surrounding area become stable in the long term.

In order to establish a realistic model for such an environment, a stable economy needs to emerge around this cyclical approach, keeping all inhabitants busy, nourished, healthy and satisfied with their duties and share in society. Equally, all trade with the outside world, bringing in needed supplements and accepting surpluses, needs to be sustainable and balanced.

Below, we introduce a number of concepts and modelling suggestions we consider relevant for accurately describing such an economy.

2. Scope

The scope of the model is a geographically well-defined area with all locally available “resources” (non-renewable, renewable, already built infrastructure, people). Within these boundaries, the objective is to establish an inclusive model that contains all relevant parameters, entities and transfers required for society to function within the above area, and for interactions with the outside world.

A number of spatially-explicit resource optimisation models have been developed at Imperial College, including:

- Hydrogen and CO_2 infrastructure design (funders: ADNOC, Shell)
- Bioenergy supply chains (funder: UK research councils)
- Urban Energy Systems (funder: BP)
- Bioenergy value chain model (ETI)

Out of these has emerged the concept of integrated resource flow and technology network models. These very flexible modelling frameworks are built around four main concepts:

- A spatial domain: this may be a city, region, country or wider area. It is normally divided into cells which may have regular or irregular shapes and which are used to characterise the spatially dependent properties of the system (e.g. population distribution, resource demands).
- Resources: these usually reflect renewable and non-renewable natural resource stocks and flows (e.g. sun, wind, biomass, food, natural gas, biogas, nitrogen, phosphorous, water in different qualities), wastes (e.g. sewage, CO2) and energy service demands (e.g. power, heating, cooling). They may be characterised by local availability, local demand, availability to import from a hinterland, cost, etc.

- Networks: these serve to transport and distribute resources inside and outside the domain and may include transport networks, gas pipelines, power grids, water networks and so on.
- Technologies/Processes: these are used to transform resources into a useful form(e.g. a digester which consumes waste and produces biogas and digestate, a CHP engine which consumes gas and produces heat and power; a water treatment facility that consumes waste water and power and produces potable water). Technologies may come in different scales reflecting different degrees of centralisation or decentralisation.

This flexible formalism allows us to model a large variety of inter-connected resource systems. In the context of the Ecological Sequestration Trust programme, a model is to be developed based on these concepts which will be suitable for:

- Capturing the interactions between diverse resource systems (sun, water, nutrients such as N+P, and carbon in various forms).
- Connecting the resource flow system with soil and biomass yield models (e.g. pedotransfer functions) that optimise agricultural productivity and quantify the energy conversion potentials of these systems.
- Integrating all flows with human supply/demand systems to map the generation of overall societal benefits and costs of different systems.
- Quantifying the cost and ecological benefits of alternative settlement and resource-technology systems which aim to close resource loops (e.g. CO2 sequestration from heat/power production via algal systems which in turn produce energy products and fertiliser).
- Exploring the fates of anthropogenic wastes and their impacts on surrounding ecosystems.
- Calculating the trade-offs of different resource technology systems and policy options with the goal of long term system stability,.
- Application to three different regions of the world (e.g. China, India, Rwanda), demonstrating holistically, optimised settlements with associated resource conversions and management systems.

To avoid creating a “nice but incomplete” world it is important not to limit the modelling effort to the objectives of carbon sequestration, nutrient cycling and other aspects related to natural resource stocks and flows. Instead we intend to model the entire “economic system” with all relevant exchanges and processes, to the level of detail required to capture approximately 90% of resource flows. Given the limited geographical scope of each system, we estimate this to be feasible, inferred from preliminary economic modelling work done by IIER.

2.1 Input-to-output relationship

The relationship between inputs and outputs will be multidimensional. Simply put, the model will run based on a system of available input and output flows at a given time t_0. The system will develop based on the available stocks and flows of the resources and energy available to the society. System process flows and agent behaviour will shape it towards a status at a predefined end period t_n, with defined time-scale intervals in between t_0 and t_n . The outcome in each time period will be dependent on selected parameters including:

- The occurrence of processes in all defined systems
- The state of throughputs in human and natural systems
- The status of infrastructure (including all ecosystems) described by pools
- The number of supported humans and their characteristics (health, economic status, occupancy etc.)
- The status of natural ecosystems (productivity, ecosystem services)
- The equilibrium state “health” of the society (inherently stable, inherently unstable)

The outcome of the model is not meant to capture an optimal functioning of processes, but a realistic approximation of reality, whereas most processes perform in a suboptimal fashion and regular discontinuities occur. Therefore, all processes and agent behaviour will be subject to variability and each starting point can have many possible outcomes, i.e. in the end there will be a range of situations emerging from the original point. The range of situations and potential outcomes will be represented by a probability distribution. By capturing such a range of outcomes it becomes possible to measure how events affect societal resilience and stability over time. That includes both events on the human side, including technologies and policy decisions, as well as the natural side such as depletion of resources or disruptive weather.

3. Key model components

The model can be described as an interaction between five different components.

- Resource conversions are linked as process chains with connected pools, drawing from and providing output to other components (individual systems are represented by "process bundles")
- General natural input is provided from solar flows and weather systems
- Agents are a separate layer interacting with physical flows via (physical) markets based on labour hours
- The external world provides for imports/export transactions including resource and energy subsidies
- Policy decisions or rules are introduced by a "strategic planner"

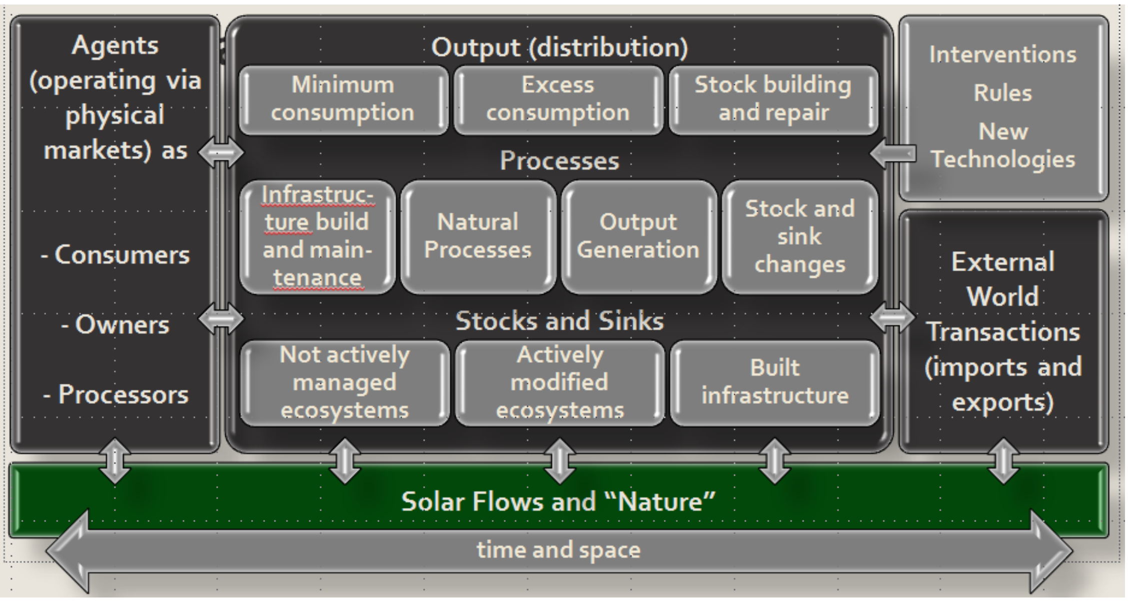

Figure 1: broad overview of model components

From our perspective, it should be feasible to limit the description to those processes and outputs in a society which produce approximately 90% of vital outputs. The remaining 10% can be assumed as others without detailed specification, as long as they do not form vital inputs that could impede or stop other key delivery systems from functioning.

Below, we will outline a summary of the key components of the model. Please note that this is not yet a final full description and requires further discussions and revisions.

4. The agent interaction component

The agents in the model will have three main roles in the model. All agents will be a consumer of goods and services, most will be participating to the labour market, and some will be owners of infrastructure. The key parameters of the agent's model are:

- Population, numbers and age distribution
- Capabilities and needs, health status and perceived happiness
- Association with processes as producers (operators of processes) or consumers (e.g. education)
- Participation rate and type (i.e. number of humans being only consumers)
- Ownership of infrastructure, goods and stocks
- Birth/death/migration model (to achieve a balanced economy)
- Input required to educate and train for various capabilities
- Initial status and vectors required to achieve a balanced economy
- Valuation of available goods and services
- Spatial location of residence and work

In order to correctly represent the long-term viability of cycled systems, we strongly discourage modelling the "economy" of such a world based on money, but rather on physical interactions between participants and systems – which can later be complemented with a monetary component. That way, distortions from market imperfections – for example the insufficient assignment of a price for externalities – can be avoided.

Thus, instead of using money as the baseline, we suggest modelling the entire "economy" on a non-monetary basis using a labour hour based value of exchange between agents. Every agent will receive a labour hour income based on their labour input in specific processes, which is "spent" on a virtual goods and service market. Both labour salaries and market labour values are adjusted from their direct input value to compensate for effects of rent from ownership, previous effort of schooling, and overall scarcity and abundance of goods, resulting in a quality adjusted labour hour quantity (QLH). The model will, following these roles, encompass four different markets, a labour market, a skills and capabilities training market, a goods and services market, and an infrastructure market for ownership.

As described above, the entire ecosystem should be modelled under the assumption that money exists as a facilitator of transactions, but "prices" of exchanges should be formed according to underlying physical entities. This removes the risk for distortions from arbitrary value assignments and also removes the need for inflation management as part of the model. However, QLH "currency" derivations in the model will be built based on economic theories of supply and demand, such that at any stage it can be supplemented with a monetary component. Equally, credit should be optionally possible in the system, shifting accumulated resources/inputs/process capabilities from participants who have accumulated beyond their needs to those who might benefit more.

4.1 Example of QLH calculation

To illustrate how labour exchange value would work in the model we introduce two agents, A with low skill in performing a certain task set, and B with a high skill to perform the same task set. Also, agent B happens to own part of the equipment required to produce the output of the process, thereby earning an ownership rent. As a basis both agents provide 8 hours of labour input. Normally this would result in a set return of 6 Quality Adjusted Labour Hours, but because Agent B can produce twice as much as the low skill baseline, he earns a gross 12 QLH. In addition, he also earns an additional 2 QLH gross in rent. Finally, to calculate the net valuation of labour output, and thereby also the labour income actually provided, a scarcity adjustment takes place dependent on a scarcity index from relative supply and demand. In this case the good is stated to be relatively abundant, at a scarcity index of 0.8. Hence respective QLH earnings are adjusted by a factor 0.8, resulting in a net QLH income of 4.8 for agent A and 11.2 for agent B.

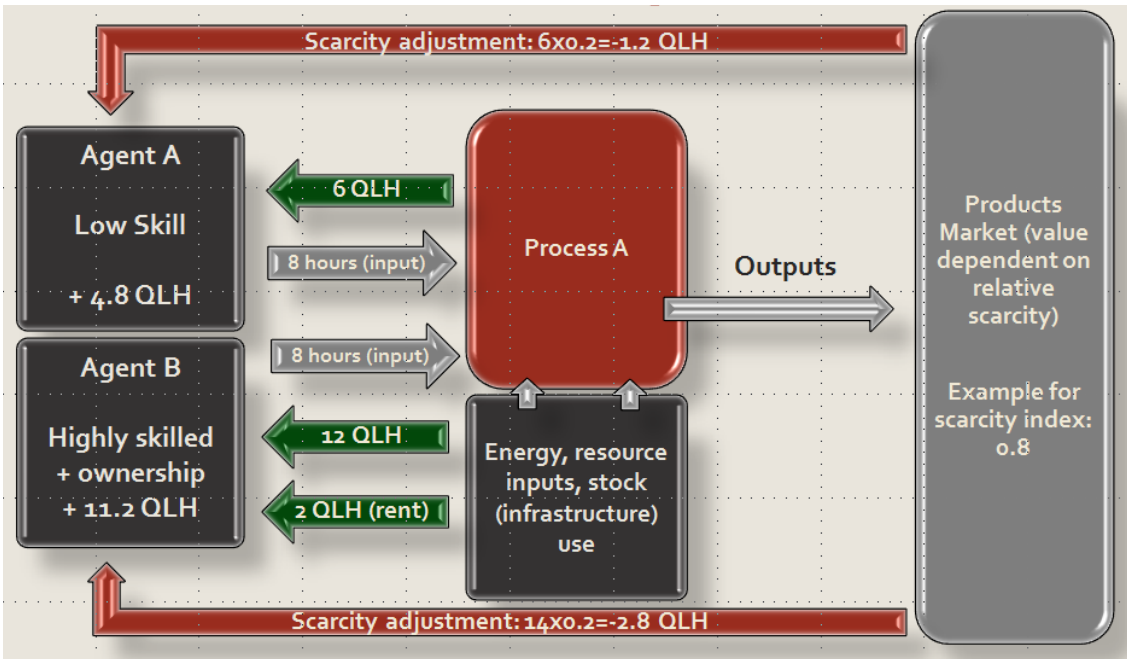

Figure 2: Example of QLH calculation

4.2 Policies

The objective is to establish an environment that is stable and resilient in the long run in many ways – not only from a perspective of resource availability, but equally in the sense that no agent or group of agents or location ends up accumulating resources in a way that is unsustainable for others. Ideally, the model would allow for a wide range of economic, social, and environmental policies, both to study the past and effects of future policy introduction. In case of unsustainable wealth accumulation, for instance, mandated redistributions could be placed to restore balance (taxation). Such policies can be set at the user level individually or as a set of scenarios with an appropriate baseline for the given locality under study.

4.3 External Trade

Imports fill the gaps in output delivery which is not covered by local inputs or agent action. It may include resource inputs, but equally technology that is delivered, and may well extend into human services through external knowledge or migration. Exports, in turn, offer the ecosystem the ability to supply other ecosystems with outputs or services which are available beyond local need but are in greater demand elsewhere. The trade of these will take place based on external supply and demand curves that determine relative valuations. In a slightly more complex fashion, migration from and to the outside world will be allowed, influenced additionally by local cultural factors.

Overall, such exchanges need to be balanced in three ways. First, the assumed value (non-monetary) is equivalent in both directions and that no long-term trade deficit or surplus emerges. Equally, it must be ensured that no outputs requiring non-renewable inputs permanently leave the area in a model where 100% cycling is suggested. Finally, supply and demand curves should be sufficiently complex to enable insights into the sustainability of goods and services obtained from the outside world, so that local pollution and unsustainable reliance is not outsourced. The model needs to be able to operate with multiple supply curve scenarios for globally available key inputs.

5. Resource Conversions

The basis of the model is the physical world, where processes of any kind turn inputs into outputs. Ideally, all natural and human processes relevant to describe the dynamics of a human ecosystem are included. To describe these processes three object types are envisioned:

- Processes, which describe how changes in the system occur, requiring inputs and providing outputs. These are clustered in a number of types.
- Flows, which denote a given instance of an input or output at a specific time and place.
- Process bundles, which describe the system boundary from all processes contained therein for any subsystem (forest, industrial sector etc.)

Individual subsystems that are normally distinguished, such as ecosystem types or industrial sectors, will be represented by bundles of processes and pools. These are constructed to enable disconnection of a subsystem by either making all outputs exogenous, all inputs/output flows from and into that system part of the external world, or by partially to entirely cancelling that system to the overall model to see the effects of a subsystem failure on the larger system model. In this manner a static model run of a subsystem can be done permitting comparison and conversion between results of other models and the Ecological Sequestration Trust's Model.

5.1 Resource Conversions - outputs

The key deliverable of the model to society is a set of predefined outputs (which can vary in different scenarios and over time). These outputs include goods and services of final consumption, , secondary process inputs, waste recycling processes, and the rebuilding of resource pools including restoration of ecological systems. All outputs have in common a number of interconnected dependencies:

- Processes, including process energy and capabilities and/or available time of agents (individuals/groups), who in turn require other outputs to lead their lives
- Other outputs that get introduced into the process (i.e. outputs at an earlier stage); again the resource-technology framework automatically captures the relationships between resources in an overall value chain.
- Infrastructure (i.e. an aggregation of previous inputs) required for processing and movement of resources

Equally, the process and after-use related “waste” needs to be measured and fed into other processes that capture those wastes and bring them back into the system, or losses into the environment need to be accepted and quantified. In our system, all wastes are also resources, some of which might be converted into other, more useful resources.

5.2 Resource Conversions - Renewable Inputs

Renewable inputs include all inputs into the “economy” that are provided repeatedly on an on-going basis and where their use can be quantified on a sustained yield basis. The key renewable inputs into each ecosystem are of solar origin, including sun, wind, water cycles and biogeochemical cycles that are not controlled by humans but potentially influenced by them.

Examples for other renewable sources might be geothermal energy and some fast-regenerating mineral deposits. All of these are modelled as a special subset of resources that arise on a regular (or seasonal) basis.

5.3 Resource Conversions - resource pools and final sinks

All resource pools that are finite in meaningfully available quantity and quality fall into the non-renewable category – like fossil energy deposits, mineral ores, topsoil , and fossil water reservoirs..

Sinks, irrespective of type, are final destinations of waste (materials and heat) where they become largely irretrievable for human effort, or only at great expense. It is important to accurately determine the initial status of sinks which require remediation or restoration, for example, excessive carbon dioxide concentrations in the atmosphere or pollution of water bodies. Resources that must be imported into the system boundaries will be described by supply curves and metrics such as cost and GHG inventories.

5.4 Resource Conversions - Processes/Technologies

Processes/Technologies are all human-controlled and natural activities that convert and transfer resources and other pre-processed inputs into outputs, typically including energy conversions, the time use of certain agents and the application and drawdown of technology (infrastructure).

Each process that leads to an intermediate and/or final output needs to be defined with the inclusion of multiple process pathways where they exist. Key properties of processes are:

- Renewable and non-renewable inputs, and outputs from previous steps
- Agent or agent group actions, where time and knowledge is applied to a process
- Use of infrastructure (which again is based on inputs)
- Outputs
- Waste (recyclable and non-recyclable ending up in sinks)
- Externalities beyond waste that impact system functioning

Transportation services are part of processing, as are activities to ensure the stability of the ecosystem, including the restoration of damaged environments.

5.5 Resource Conversions - Infrastructure

This describes all the “structural technology” required to produce an output (goods or services) and consists of the physical aspects of it, including machinery, buildings, roads, other infrastructure), but also natural systems such as forests, wetlands, and grasslands.

It should be possible to include soil on arable land as one type of “infrastructure” with properties requiring restoration after use (withdrawal from nutrients, runoff, etc.).

For each infrastructure element the following aspects should be determined:

- Required inputs into the creation of the infrastructure (from outputs and agent services)
- Inputs into the operation of the infrastructure
- Inputs into the renewal of the infrastructure (life expectancy, maintenance, repair)
- Inputs and outputs at the point of discontinuation of use (decommissioning)
- Waste and other externalities from the creation, operation and decommissioning of infrastructure

It is important to accurately determine the initial status of the infrastructure in pre-existing environments. Infrastructure that is no longer in use can be run in “drawdown” mode, or – where new technologies are introduced, infrastructure can be reclaimed or retrofitted for a different use.. For infrastructure which is to be used indefinitely, drawdown on existing infrastructure should always be balanced with recreation.

The model should be built in a way that interdependencies and relationships between processes become apparent (nested process chains). This allows for increased model accuracy and resiliency.

6. Nature – and natural systems

The model approach treats natural systems and processes like human-defined elements in their function of providing output via conversion of input. The baseline for all ecosystems modelling comes from natural cycles including weather, nutrient cycles and other natural forces that affect the ecosystem under observation. The processes related to these inputs (like biomass growth, water transport, and other environmental services,) will interact with “man-made” components.

The dimensional view encompasses terrain (surface area, rock, arable and non arable land, including the stored minerals in the earth’s crust), water bodies (salt- and freshwater), forests and other natural areas, the atmosphere, and all services provided by these systems (supplier of inputs, processor, sink).

7. Modeling challenges – possible solutions

One key challenge to a modelling effort with such a broad scope is the lack of reliable and consistent data sources, particularly when it comes to process information for vital societal processes. Another issue that must be overcome when setting up local models is the limited availability of high level granular data.

We suggest to apply a flexible model of input management that we have conceptually developed for a global resource flow model. It has a number of properties:

- Flexible interfaces to input data sources (data warehousing approach), allowing to easily plug in relevant data sources with the ability to link, import and manually enter data depending on source with an integrated review protocol (sign-off)
- A data model which allows inputs from various sources simultaneously and the flexibility to model multiple outcomes based on multiple sources.

- A source qualification system which provides simple online review capabilities and the ranking and weighting of data sources
- The ability to fill data gaps with "closest approximation" from other data sources or locations until better data becomes available (for example – if a city doesn't have sufficient data on the energetic quality of their buildings, it is feasible to make a fairly reasonable assumption on the average standard based on weather data, sector energy consumption and local standards and expectations)

7.1 Model Validation

In a model of such large complexity external and internal validation is of key importance to assure meaningful outcomes. In the project, several testing procedures will be standardized and applied, including statistical procedures, triangulation of calculation approaches and data sources, and overall validation from empirical data and past events.

The overall model will be validated based on simulations at multiple scales. Accuracy will be determined based on comparing development in the model over time with historic data. The scales at which the model will be tested and applied includes a rural village that is self-sufficient for 90%+ of its resources from the local ecosystems, a medium size city with nearby hinterlands resembling populations where the model is to be implemented by the EST, and a large industrial nation where large amounts of historic data are available such as the United Kingdom. Similar validation efforts will be carried out for individual subsystems.

8. Other parameters

In order to be realistic in the entire model, a number of key parameters have to be introduced which define the reality of the "economy" under analysis.

8.1 Level of cycling

In most cases, the final reality of such a newly created ecosystem is not one of full cycling. Some inputs – like fossil fuels – might still be present for extended periods and thus used.

The model needs to be able to work with different degrees of cycling from 0-100% for the entire system or sub-systems as one key boundary. In a 0% scenario, no cycling takes place and all waste and losses of the processes go into sinks. In a 100% cycling situation, the society is not allowed to generate more waste than can be cycled through the system. Thus, system processes continue without the accumulation of wastes that otherwise disrupt system functioning.

8.2 Realistic optimum/Resiliency

Models should be built in a way to allow for “imperfection”, both in the availability of inputs (for example sunlight, wind, water), but also in the process stages, where human error and excess waste are rather the norm than the exception. This should be introduced in multiple ways

- Variations in inputs (predefined and stochastic variation)
- Realistic optimum for processes (related to human error, inadequate equipment, etc.)
- Disasters – rendering parts of process chains, agents and inputs unavailable for certain periods of time

One aspect of the model should be the ability to predict a society’s resiliency based on these parameters and the method of nesting processes that deliver vital outputs. By running Monte Carlo simulations with “disturbances” in multiple subsystems it should become clear as to how tolerant the society reacts to those problems.

8.3 Tolerated inequality

Over time, it is likely that wealth and benefits will accumulate unsustainably in a model as they do in real societies. Each agent, however, needs to be able to attain an “acceptable” standard of living for him/her and his/her dependents, which does not deviate from the average by a certain allowed deviation factor (i.e. income spread).

Thus it becomes relevant to define the ratio of tolerated inequality in a number of ways:

- Minimum level of outputs available to agents at the “lowest rank”, i.e. definition of the outputs (food, shelter, societal services, etc.) that form this minimum
- Maximum tolerated inequality between agents of the lowest and highest rank in a society over time (similar to GINI coefficient, but based on available outputs and not money)

The model needs to be able to evaluate all situations where such accumulations of wealth take place and compensate this with “taxation”, i.e. a shift of resources according to a clearly defined and stable pattern or redistribution.

8.4 Time

One of the most important dimensions of modelling is time – in multiple ways:

- Ecosystem development can only be monitored over longer periods, as many effects – both in physical flows as well as agent properties – can only be seen over time, as a series of successional stages and the potential for occasional disturbance events. The model needs to be able to incorporate temporal variability and allow for perturbations.
- Delivery of many services is time critical – for example, many inputs (food, resources, water, etc.) need to be available all year long, not just at times of harvest, and appropriate storage needs to be provided if flows are intermittent. This is even more true for critical delivery systems such as electrical energy, where accurate matching of supply and demand has to be timed to the minute

In order to support the time dimension, each input and flow needs to be assigned respective properties and scales.

In this model we shall have multiple temporal scales: annual, to reflect larger scale processes including the evolution of infrastructure and ecosystem development, and hourly to seasonal (e.g. 4 seasons in a year) to reflect the need to ensure balanced operation of the system over the annual cycle (e.g. weather and electricity production).

9. Model interactions

The model we envisage is supposed to deal with many sources in order to be able to improve over time and to be used in various environments. In the process of model development and implementation several actors are to be involved in a number of stages. For the core model development collaboration will occur with specific domain experts, to ensure that for all subsystems no key relationships are left out, and to bring in the best available understanding and data in modelling a subsystem. In each locality where a pilot design project will be carried out, interactions between local experts, pilot project members and the modelling team are anticipated. The goal is to craft the specifics of their environment into the model as well as iterate back and forth over operational design inputs. These range from details over specific policies relevant to the local environment and the feasibility thereof, the technologies and their variants that have potential for implementation, as well as scenario design in the assumptions over global resource availability and world developments that result in supply curves.

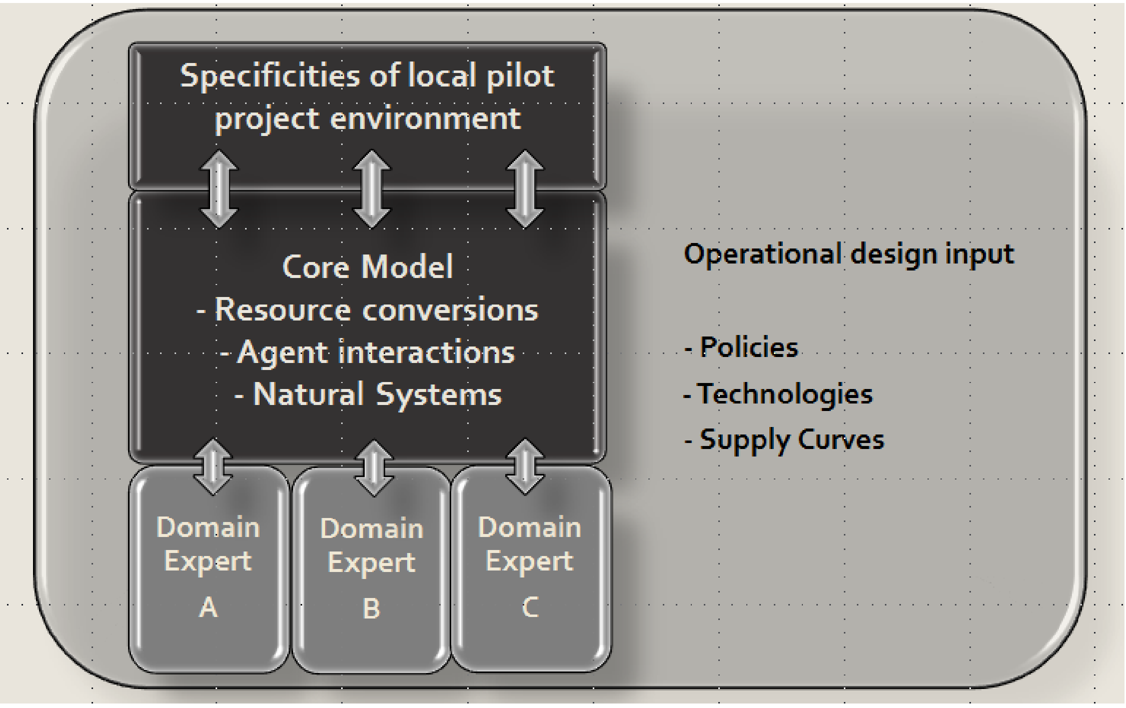

Figure 3: Model workflow between generic core model work, domain expertise, local pilot project information, and operational inputs.

9.1 Domain knowledge

To capture specific mechanics of subsystems in the required level of detail we will work with a wide variety of domain experts. The collaboration with these experts extends to provide knowledge on model relationships and data. Currently, identified domain experts are as follows:

- Harald Sverdrup, Lund University – Soil Systems/Resource Supply Curves
- Goetz Richter, Rothamsted Research – Agriculture
- Marcus Lindner, European Forest Institute – Forestry
- Geoffrey Hammond, University of Bath – Life Cycle Analysis Data
- Kristin Vala Ragnarsdottir, University of Iceland – Macro Health
- Peter Smith, University of Aberdeen – Ecology
- Graham Hillier, Center for Process Innovation – Process technologies
- Wouter Buytaert, Imperial College – Hydrology
- Julian Allwood, Cambridge University – Resources/Energy
- Vicky Pope & Chanqqui Wang, UK Met Office - Climate
- Jeremy Woods, Imperial College – Biomass & Food Supply

In addition to the above, there are a number of complementary key domains on which subject experts are to be identified in the first quarter of 2012.

10. Timeline (IIER deliverables)

Based on our discussions, we are aiming at an aggressive timeline with a significantly larger team to speed up data collection and verification. With this, we should be able to complete the first part of the project (model available and tested for one location) within 12 months

• Specifications and draft relationship model	Q1 2012
• Refine of relationship model and first draft of data model	Q2/3 2012
• Data gathering for key underlying processes	all 2012
• First rough prototype	Q1/2013

This approach is based on a parallel approach, i.e. data gathering is already initiated during the data modelling phase, and implementation begins half-way through the data gathering phase.

11. Timeline (Imperial College Deliverables)

A project of this nature should follow a rapid prototyping approach, aiming to deliver a prototype with 70-80% of functionality as soon as possible and then use this prototype in a number of case studies to refine the specification and develop the tool further. On this basis, the following timescales are envisaged:

i. **Month 1-3:** Refine the functional and technical specification of the tool. Work with stakeholders to define the required functionality more clearly. This would ideally have a kick-off workshop with a range of potential users/interested parties. Deliverables: detailed specification, including some simple test cases.
ii. **Months 3-9/3-12:** Develop the first prototype, based on the four element framework described above. Deliverables: prototype model with basic documentation.
iii. **Months 9-12/12-15:** Test the prototype on some stakeholder-defined case studies. Hold a second workshop to demonstrate interim functionality and results and refine the specification. Deliverables: results of test cases; user feedback; refined specification.
iv. **Months 12-18/15-21:** Refine the model and test it on more demanding applications. Deliverables: Working model and documentation, results of more demanding applications.

In parallel

v. **Months 12-18:** Collect data for the three regional pilots; explore potential system solutions using the model for these pilots. Deliverables: alternative solutions for the three pilot studies, along with quantified metrics.