The Ecological Sequestration Trust Modelling Suggestions – Draft

Revision Date:	October 7, 2011
Revision:	V0.9
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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 documents 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 and its agricultural, forest and supply hinterland 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 which are required for a functioning of the societies within the above area, and for interactions required with the outside world.

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

- Hydrogen and CO2 infrastructure design (funders: ADNOC, Shell)
- Bioenergy supply chains (funder: UK research councils)
- Urban Energy Systems (funder: BP)

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 materials and fuels (e.g. biomass, food, natural gas, biogas, nitrogen, phosphorous, water in different qualities), natural resources (e.g. sun, wind, rain), 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 move resources around the domain and may include transport networks, gas pipelines, power grids, water networks and so on.
- Technologies/Processes: these are used to inter-convert resources (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 are in the public domain) which will be suitable for:

- Capturing the interactions between diverse resource systems (sun, water, nutrients such as N+P, carbon in various forms).
- Connecting the resource flow system with soil and biomass yield models (e.g. pedotransfer functions) to optimise the agricultural productivity and connect the energy conversion and agricultural 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 tightly (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 over choosing different resource technology systems in combination with policy options, in their benefits and costs to different parts of the system to explore the feasibility of stability.
- Application to three different regions of the world (e.g. China, India, Greece, Rwanda), demonstrating a holistically optimised settlement with its resource conversion and management systems.

To avoid creating a “nice but incomplete” world it seems important to not limit the modelling effort to the objectives of carbon sequestration, nutrient cycling and other aspects related to natural sources and sinks. Instead we should try to model the entire “economic system” with all relevant exchanges and processes to the finest degree possible. Given the limited geographical scope this seems feasible, applying economic modelling concepts developed at IIER.

2.1 Input-to-output relationship

The relationship between inputs and outputs has to be multidimensional, but simply put, the model will take any status (including current input and output flows) at a given time t_0, and by means of processes and agent behaviour shape it towards a status at a predefined end period t_n, with defined intervals in between. The outcome would have to be, dependent on selected parameters:

- A status of infrastructure (including all ecosystems)
- The number of supported humans in the area
- The equilibrium state (inherently stable, inherently unstable)

As all processes and agent behaviour will be subject to variability, 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, some with higher, some with lower probabilities.

3. Basic assumptions

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, but with the assumption of money being present as an enabler of simple and smooth exchange between agents. The key modelling components are inputs, outputs and transactions which get shifted between physical entities (sub-locations) and agents in the model. Transactions can be processes, services or other exchanges (trade). In particular the movement and interconversion of resources through and around the system will need to be reflected in these transactions.

4. Long-term stability and balance

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. Wherever that is the case, mandated redistributions need to take effect to restore balance (taxation).

Equally, exchange with entities outside the boundaries needs to be balanced to avoid long-term instabilities in any one direction.

5. Key model components

Below, we will introduce the key components of the model as we see them at this point. Please note that this is a first draft which needs further discussions and revisions.

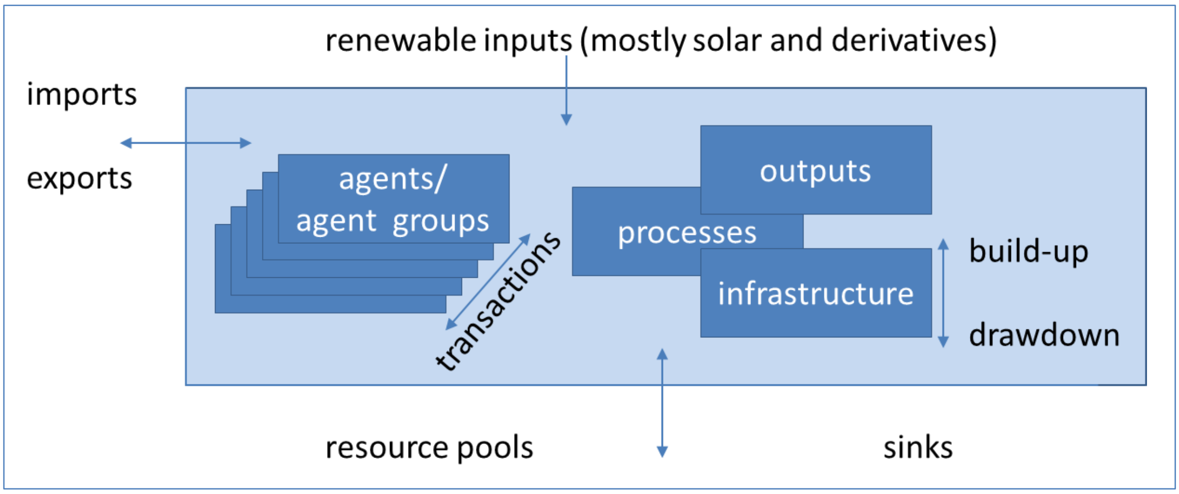

Figure 1: broad overview of model components

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, and assume others without detailed specification, as long as they do not form vital inputs that could stop other key delivery systems from functioning.

5.1 Outputs

The key deliverable of the model society is a set of predefined outputs (which can vary in different scenarios and over time). These outputs range from services to goods of final consumption to inputs into processes, to recycling, and to contributions to the rebuilding of resource pools and damaged ecological systems. These can be modelled as a particular class of resources in our formalism.

All outputs have in common that they require a number of contributions:

- 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 Renewable Inputs

Renewable inputs include all inputs into the “economy” that are provided repeatedly on an on-going basis and where their use does not negatively affect the source or only in such a minimal way that it can be neglected.

The key renewable inputs into each ecosystem are of solar origin, including sun, wind, water cycles and biological cycles that are not controlled by humans.

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 (Non-renewable) resource pools and final sinks

All resource pools that are finite or finite in a meaningfully available quality fall into the non-renewable category – like fossil energy deposits, mineral ores, topsoil on actively farmed land, fossil water reservoirs and biomass that is withdrawn for human use, which remove nutrients over time.

Sinks, irrespective of type, are final destinations of waste (materials, heat) where they become largely irretrievable for any human effort, or only at great expense.

It is important to accurately determine the initial status of damages to sinks which require fixing, for example excessive carbon dioxide concentrations or pollution of water bodies.

Resources that must be imported into our system boundaries will be described by supply curves and metrics such as cost and GHG inventories.

5.4 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, in certain cases even with multiple process pathways where they exist. Key properties of processes are:

- Inputs: 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

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

Food and – managed and unmanaged – biomass production is also included in the process view (see 5.8), as are natural processes such as dune water filtration, and is the delivery of all services to a population (including health services)

5.5 Infrastructure

This describes all the "technology" required to produce an output (goods or services) and consists of the physical aspects of it, like machinery, buildings, roads, other infrastructure), but also natural systems.

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

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

Infrastructure that is no longer used can be run in "drawdown" mode, or – where new technologies are introduced, a build-up is required. For infrastructure which is to be used indefinitely, drawdown on existing infrastructure should always be balanced with recreation. It is important to – for already existing environments – accurately determine the initial status of the infrastructure.

5.6 Agents/Agent Groups

Human inputs form the vital part into the entire economy, both from a knowledge and actual time (labour) perspective. It might be sufficient to introduce them as agent groups associated to processes (and output consumption), The key parameters are:

- Capabilities and needs, health status and perceived happiness
- Association with processes as producers (operators of processes) or consumers (e.g. education)
- Participation rate (i.e. number of humans being only consumers)
- 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 balance

5.7 External Exchange

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. As mentioned above, these can be described by "supply curves".

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..

Overall, these exchanges need to be balance in two ways, first in that 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.

5.8 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, but also negative impacts) 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 capabilities of these terrain types (supplier of inputs, processor, sink).

6. Monetary system

As described, 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, monetary units should be established as an overlay on the entire system of transactions, allowing the introduction of monetary markers at any point in time. 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.

7. Modelling 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. Further problems exist when setting up local models is that granular data is unavailable for many aspects.

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 sources (data warehousing approach), allowing to easily plug in all possible data sources with the ability to link, import and manually enter data depending on source with an integrated review protocol (sign-off)
- An data model which allows to keep inputs from various sources simultaneously and 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)

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 lose more resources and energy than can be harnessed or cycled.

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/herself 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 equality 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, unearthing many risky and unwanted developments. The model needs to be able to monitor those and to allow for corrections
- 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. Data Sources

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. Initial providers of flow data are assigned as follows:

- Agricultural models: Lund University (official partner), University of Vermont (IIER suggestion)
- Forestry model: European Forestry Institute
- Urban model: Imperial College SYN-CITY model
- Model integration: University of Iceland (Kristin Vala Ragnarsdottir)
- Industrial and raw materials model: IIER, Swiss Technology Institute LCA data (ETH - IIER suggestion)
- Agent model: IIER
- Economic flow model: IIER
- Weather data: Local meteorological units (hourly data)
- Energy systems model and data: IIER database, local utilities

However, all these input sources should only be one type of source which can be replaced and augmented over time as new and possibly better data becomes available (please see 7.)

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

- Development of further details of model (conceptual) October 2011
- Data Modelling December 2011
- Data gathering and manual calculation of sub-models July 2012
- Model implementation and optimization with 1 target city October 2012

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.