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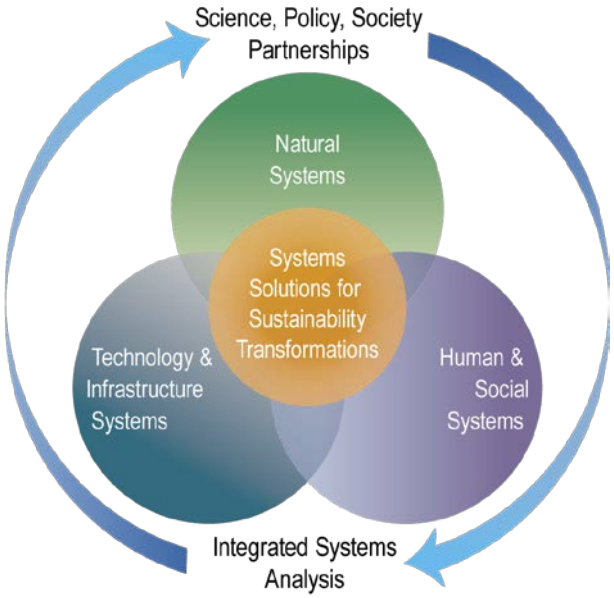
IIASA Research Overview

A. Introduction and research framework

As a leader in applied systems analysis, IIASA is able to integrate natural, social, and economic systems to produce independent, interdisciplinary research into real-world problems. The institute's collaborations with research institutions and policymakers around the world ensures the highest quality, most relevant science.

IIASA has a long and successful history of developing systems-based, integrated solutions and policy advice for some of the world's most pressing problems, from poverty to climate change. The Research Plan 2016-2020 responds to an increasingly globalized world that is characterized by fundamental shifts in economic and political power, growing global environmental problems, and potentially explosive social conflicts.

The research framework (below) provides both the foundation for the institute's research direction and the necessary flexibility to modify IIASA activities to accommodate changing scientific or policy priorities.



The IIASA research framework

This framework moves away from the idea that problems (such as climate change) are separate from drivers (such as population growth) or from impacts (such as environmental degradation). Problems,

drivers, and impacts are in fact closely related elements of systems analysis and achieving true sustainability requires an approach that can link diverse dynamic systems.

B. Research Programs

Currently nine research programs carry out research at IIASA into the dynamics of global change. A brief overview, including recent research highlights, of each of these individual programs is provided below.

1. Advanced Systems Analysis Program (ASA)

ASA's mission is to develop novel methods and applications for systems analysis, thus ensuring IIASA remains internationally recognized as the leader in systems analysis. The program operates by means of small-scale exploratory collaborative interdisciplinary projects.

ASA's research deals with complex socio-environmental systems, organized around three areas

- Optimal behavior of systems
- Interdependencies within systems
- Resilience of systems

Optimal behavior of systems

Stylized models that simulate phenomena in complex social, economic, and environmental systems are used to explore optimal behavior in terms of selected objective functions that define decision maker's preferences. These models are mathematically tractable, which allows the impact of uncertain parameters on optimal decisions within the modeling frameworks to be identified. Mathematical tractability also allows the analysis of a complete set of decision options and outcomes depending on the model's parameters and comparison with the optimal solution. Stylized models are computationally efficient tools for (a) exploring various assumptions used in larger models, and (b) investigating complex dependencies and feedback. This approach is currently being utilized to examine topics such as: drivers and impacts of long-term economic growth; size-structured population dynamics and trade-offs between economic and ecological objectives; social interactions; risks and optimal insurance schemes; and the food-energy-water nexus under uncertain environmental and economic conditions.

Interdependencies within systems

Various multi-agent systems, such as ecological food webs, energy, and transport infrastructure, financial systems, and social interactions, can be represented as networks in which links indicate interactions between the agents. For example, predator-prey relationships, electricity or financial flows, or views among people. All these processes can be studied by analyzing their underlying networks. ASA is investigating: (a) the role of indirect connections, (b) cascading failures, often referred to as systemic risk, and (c) the relationship between complexity and stability of network dynamics. This latter has direct applicability to: vulnerability of ecological food webs; systemic risk in financial systems; indirect effects in ecosystems and economic systems; and entropy-based sustainability metrics.

Resilience of systems

Given the large uncertainties associated with how complex socio-environmental systems function, decision makers need information on how to improve the resilience of these systems to possible shocks and under various development scenarios. ASA's research uses advanced learning from the past to extrapolate into the future, and identifies the pre-cursors of the occurrence of certain events, such as the collapse of networks due to systemic risk. The socioeconomic development of regions and countries is at heart of the ASA research on resilience. Using agent-based modeling, the behavior of social and economic agents can be explicitly modeled allowing examination of the ways agents respond to changes in the environment in which they operate.

Maximum principle for infinite time horizon economic growth problems

Problems of the optimal management of resources include extraction of a non-renewable resource; allocation of resources and optimal investment strategies. When considered in a stylized modeling framework these take the form of optimal control problems on an infinite time horizon. Solving such problems usually involves the "maximum principle" – a theory that provides the necessary conditions for optimality. At the moment there is no universal and complete theory available for optimal control problems on infinite time horizons, with various modifications of the maximum principles developed for various special cases. However, ASA researchers, Sergey Aseev and Arkady Kryazhimskiy (see References) have developed a new version of the maximum principle that can be efficiently used to solve problems of optimal resource management and allocation.

Challenges and Opportunities of Broader European and Eurasian Economic Integration

The ASA Program oversees the IIASA Eurasian Economic Integration Flagship project, which deals with the complex issues of economic cooperation between countries of the Eurasian continent. The establishment of the Customs Union of Russia, Belarus, and Kazakhstan (RBK-CU) in 2010 and its subsequent evolution into the Single Economic Space (SES) in 2012 represents a prominent current example of regional economic integration in northern Eurasia. Authorities in the RBK-CU/SES envisage deepening this regional integration even further by establishing the Eurasian Economic Union (EEU). Simultaneously, there has been progress in further enlarging the EU and in the development of the EU Eastern Partnership (EaP) initiative.

The international and interdisciplinary flagship project aims to discuss and analyze critical issues of economic cooperation between the enlarged EU, CU/SES and their neighbors including the key Asian players, such as China, Korea and Japan, which could lay the foundation for a broader Pan-European/Eurasian Economic Space. The two-year research project consists of a series of workshops at which specific aspects of integration will be discussed by scientists and stakeholders representing all interested regions. Follow-up synthesis reports will outline the 'state-of-the-art' in this field and reflect on different futures.

In light of recent political and economic developments around the Ukrainian crisis, the project plays an especially important role of science diplomacy, bringing together experts and decision makers from

different sides of the complex process and creating a neutral platform for open and constructive discussions.

2. Air Quality and Greenhouse Gases Program (AIR)

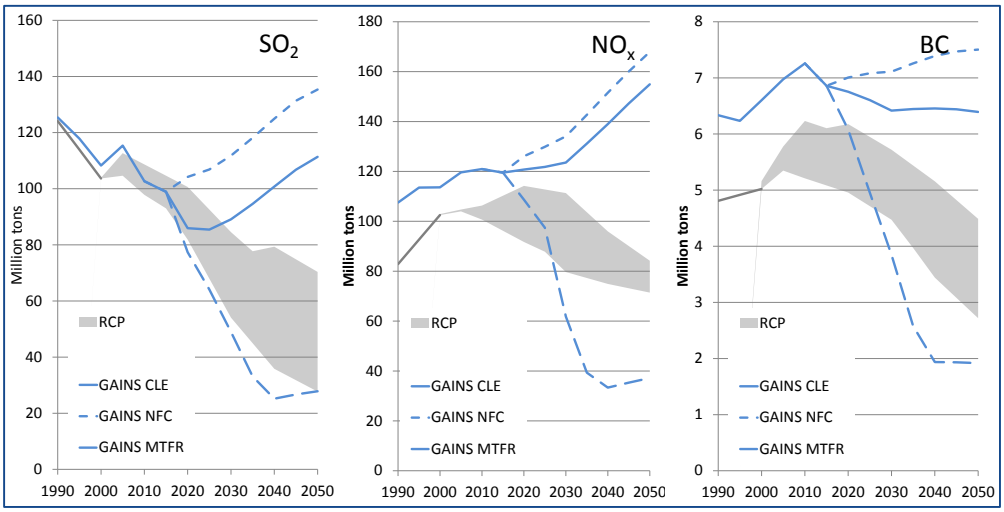
Given the current impasse in global climate policy regimes and the urgency for a quick reversal in global greenhouse gas emission trends to avoid dangerous climate change, AIR develops new perspectives to highlight measures that make cost-effective contributions to development, human health, agricultural production and biodiversity at the local scale and in the near term, and at the same time yield positive side-effects on climate change. The program develops a systems perspective of the interactions between anthropogenic activities, emission control measures, economic impacts, their health, vegetation, ecosystems and climate effects, and how they interact across different spatial and temporal scales. Fed into a common framework (the 'Greenhouse gas – Air pollution Interactions and Synergies' – GAINS model), a variety of systems methods are used to identify concrete measures that yield multiple benefits for local and global policy objectives.

These analyses are of immediate policy relevance for industrialized and developing countries. They provide scientific guidance to a range of international policy initiatives, such as the Convention on Long-range Transboundary Air Pollution, the climate and air quality policies of the European Union, the Arctic Council, and the newly founded Climate and Clean Air Coalition.

A global perspective on air pollution

The recent global implementation of the GAINS model now enables a fresh perspective on air pollution trends in different world regions. Conventional long-term projections of global air pollutant emissions in the literature that have been often used for climate simulations ignore the pivotal role of policy interventions and governance, as they assume autonomous decline in emission intensities following the assumed increase in per-capita income. As a consequence, the available global scenarios suggest air pollution to be a diminishing problem. However, while an inverse relationship between pollution and wealth (the environmental Kuznetsk hypothesis) has been demonstrated for urban SO_2 emissions in the past, such behavior is less obvious for other pollutants, and turning points, if they can be observed, occur in different world regions at different income levels. Furthermore, as experience shows, bending trends downwards required strong policy interventions, responding to public pressure and incorporating scientific findings.

The GAINS model has been used to construct a range of global air pollution scenarios up to 2050 for alternative assumptions on dedicated policy interventions on emission controls. For instance, future emissions of nitrogen oxides (NOx) could vary by up to a factor of four, between a scenario that assumes no further air pollution controls and a case in which all emission control measures that are today commercially available were fully implemented. Governance, including compliance with already agreed emission control legislation, emerges as a key factor that will determine future environmental quality (Amann *et al*., 2013).



Short-lived climate pollutants

While there has been awareness among the scientific community about the climate impacts of black carbon emissions for a long time (e.g., Bond *et al*., 2013), prevailing uncertainties about the various impact pathways of aerosols (e.g., their direct and indirect forcing) have prevented specific policy action. AIR developed a methodology to identify concrete emission reduction measures that lead to robust positive net climate impacts. As a new element, this methodology considers the co-control of specific measures on the full range of pollutants (i.e., BC, OC, CH_4, CO, VOC, NOx, SO_2, CO_2, etc.), the uncertainty ranges of their effectiveness for the various substances, and their radiative impacts.

A combined analysis of these factors identified 16 readily available measures that, together, could reduce temperature increase in the coming decades by up to 0.5 degrees compared to a baseline projection. At the same time, these measures, which focus on methane and black carbon, would have substantial benefits for air quality and public health worldwide, potentially reversing trends of increasing air pollution concentrations and mortality in developing countries (Anenberg *et al*., 2012). Published in *Science* (Shindell *et al*., 2012), these findings sparked the formation of the 'Climate and Clean Air Coalition' (CCAC), a voluntary partnership of 96 governments and the private sector to promote the 16 measures that have been identified with IIASA's GAINS model (http://www.unep.org/CCAC). Markus Amann was appointed as a member of the CCAC Science Advisory Panel.

Integrating physical and socioeconomic modeling

In collaboration with the World Population Program, AIR developed an innovative model of the interactions between population dynamics, economic growth and investments into environmental protection and their consequences on human wellbeing. The new tool quantifies the impacts of non-productive investments into air pollution control on economic growth while considering the benefits of an enlarged labor force from reduced morbidity. For the case of India, it has been found that additional investments into end-of-pipe emission control measures would lead to a slightly lower growth of per-capita GDP; however, if measured by the Human Development Index, these detriments are more than compensated by lower mortality from less particle pollution (Sanderson *et al*., 2013).

3. Ecosystems Services and Management Program (ESM)

ESM aims to improve our understanding of ecosystems and their management in today's changing world—in particular, the current state of ecosystems, and their ecological thresholds and buffering capacities.

The strategic goal of ESM is to support policymakers in developing rational, realistic, and science-based strategies for the production of food, feed, and bio-energy and other ecosystem services. By using advanced theories of applied systems analysis, new information technologies and integrated biophysical, social, and economic modeling techniques; ESM is charting possible pathways to the future by linking ecosystems, society, policy, and governance.

Climate-smart agriculture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Cattle are top global livestock emitters

By Mark Kinver
Environment reporter, BBC News

Cattle are the biggest source of greenhouse gases, accounting for more than three-quarters of all emissions from global livestock, a survey shows.

The assessment, described as the most detailed of its kind, identified Europe and the Americas as the world's epicentres of beef production.

Annually, the world produces 586m tonnes of milk, 124m tonnes of poultry and 59m tonnes of beef.

The findings appear in the Proceedings of the National Academy of Sciences.

The assessment, funded by the International Livestock Research Institute (ILRI) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), produced a global dataset of cattle, small ruminants, pigs and poultry, as well as milk, meat and eggs for 28 regions.

The findings highlight dramatic differences in livestock production around the globe

Studies by ESM (published in a number of papers in the *Proceedings of the National Academy of Sciences PNAS* (i.e., Havlík *et al*. and Herrero *et al*., 2013) and featured on BBC News – *Science and Environment*) show that livestock production is responsible for 12% of human-related greenhouse gas emissions, primarily coming from land-use change and deforestation caused by expansion of agriculture, as well as methane released by the animals themselves, with a lesser amount coming from manure management and feed production. The assessment, described as the most detailed of its kind, concentrated on the debate over the role of livestock in our diets and the search for global solutions to the challenges they present. The authors of the PNAS papers said there was not a globally uniform picture when it came to the amount of resources required to raise livestock or the environmental impact. For example, they showed that most of the 1.3 billion tonnes of grain consumed by livestock was fed to farm animals—primarily pigs and poultry—in Europe, North America, Eastern China, and Latin America. In contrast, all the livestock in sub-Saharan Africa eat only about 50 million tonnes of grain annually. With respect to emissions, livestock in South Asia, Latin America, Europe and sub-Saharan Africa had the highest regional totals. Figures suggested that ruminant animals (cows, sheep, and goats) required up to five times more feed to produce a kilo of protein in the form of meat than a kilo of protein in the form of milk. The researchers also found that the quality of an animal's diet made a "major difference" to feed efficiency and emissions. For example, in arid conditions in sub-Saharan Africa, cattle had to consume up to 10 times more feed to produce a kilo of protein than an animal kept in more favorable conditions. Such assessments show more clearly where livestock producers can improve animal diets to produce more protein with better feed while simultaneously reducing emissions. Furthermore, the projected transition of livestock systems from pure grazing diets to diets supplemented by higher quality feeds will cut greenhouse gas emissions from land use change globally by as much as 23% by 2030, while improving food availability and farmers' income.

Citizen science and crowdsourcing for improving land cover information

In the last decade, multiple global land-cover data products have been developed. But when these products are compared, there is disagreement across land-cover types. Where one map shows cropland,

another might show forest domains, for instance. These discrepancies persist even when you take differences in the legend definitions into account. The reasons for this disagreement include the use of different satellite sensors, different classification methodologies, and the lack of sufficient data from the ground, which are needed to train, calibrate, and validate land-cover maps. However, land-cover information is of fundamental importance for environmental research. It serves as critical baseline information for many large-scale models, for example in developing future scenarios of land use and climate change. Despite this fact, current land-cover products are not accurate enough for many applications and to improve them we need better and more accessible validation data.

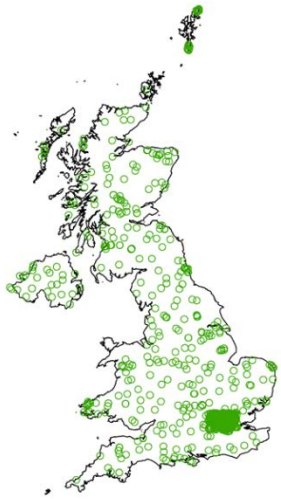


Figure 1a: Samples collected across the UK by citizens via Geo-Wiki

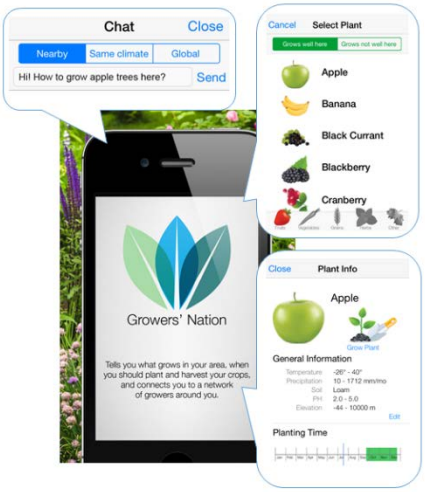


Figure 1b: Encouraging local food production through the Grower's Nation app

ESM's Earth Observation Systems group (EOS) specializes in crowdsourcing and citizen science through the Geo-Wiki system (www.geo-wiki.org). Geo-Wiki was designed to help improve our basic knowledge of land cover and land use. It is a platform that provides citizens with the means to engage in environmental monitoring of the earth by providing feedback on existing spatial information overlaid on satellite imagery or by contributing entirely new data. Data can be input via the traditional desktop platform or mobile devices, with campaigns and games used to incentivize input. Resulting data are available without restriction. Through Geo-Wiki and its multiple branches—*inter alia* livestock, biomass, and cities—citizens help us to collect data based on what is visible from high resolution satellite imagery (Fritz et al, 2013).

Data have been collected from around the world and are used to calibrate and validate land cover products.

ESM-EOS is also on the forefront of mobile app development for in-situ data collection, education and for improving food security. The Grower's Nation app, developed in collaboration with the Grower's Nation initiative of the UK Met Office, represents one example of encouraging citizens to grow more food locally by providing the information needed on what to plant in which location and how.

ESM's Integrated Modeling Cluster

The ESM Integrated Modeling Cluster was formally established in 2011 to further develop the systems analysis capacity of ESM through integrated modeling based on methodologically new and innovative tools. The four core models of the cluster have been further developed and completed with new and innovative components. The biophysical global forestry Model G4M has been adopted for REDD+ policy assessments; while the biophysical agricultural model EPIC has been expanded from a European to a global scale assessment tool. Both biophysical models provide the input data for ESM's global economic

land use model GLOBIOM that targets, not only agriculture and forestry sectors, but also includes a unique livestock component. The techno-economic engineering model BeWhere has been transformed from a local bioenergy model into a global renewable energy systems optimization model.

An impressive demonstration of the cluster's capacity in the area of functionality of systems approaches has been World Wildlife Fund's Living Forest Report which has been entirely based on the cluster's models, addressing global forest-related topics such as avoiding deforestation, forest management, biodiversity protection, greenhouse gas emissions, land-use change, bioenergy, fertilization, water demand, food security, agricultural intensification, global diet patterns, etc.

4. Energy Program (ENE)

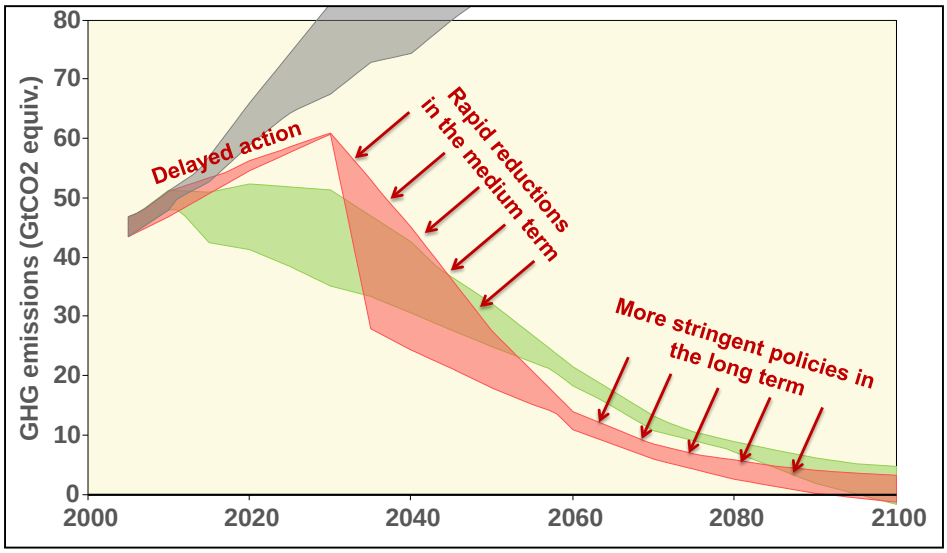
The goal of ENE is to better understand the dynamics of future energy transitions, their main driving forces, enabling factors, barriers, as well as their consequences for the social, economic and environmental dimensions of human wellbeing. The program aims to support policy making by studying mechanisms that would permit the transformation of the present energy system to one that is more sustainable. The research strategy combines basic and applied research with a focus on integrated assessment, energy policy modeling, and the development of decision-analytical frameworks for policy integration. Science-based policy advice is achieved through an *integrated* assessment and modeling of how to simultaneously address the major energy policy challenges in the areas of environment (climate change and air pollution), energy poverty (or access to affordable and clean energy for the poor), energy security and reliability. The program's niche builds upon the systematic and holistic analysis of energy policy objectives and their interactions to identify possible synergies and trade-offs. This includes the identification of salient co-benefits from meeting a range of energy-development objectives that are robust against the uncertainties of the future.

Integrated assessment of climate change

Integrated assessment of climate change and climate policy analysis has been a core research activity of the ENE program. ENE has played a central role in shaping community-wide climate research activities, including the so-called Shared Socioeconomic Pathways (SSPs). The SSPs are part of the new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. ENE in collaboration with ESM has contributed to this process both via coordination of the scenario development activities and by providing critical scientific input as one of the five Integrated Assessment Modeling groups involved in the development of the SSP scenarios. The conceptual framework of the SSPs was published in a Special Issue in the journal *Climatic Change*, and a second SSP special issue is currently in preparation and will summarize the quantitative scenario projections and storylines of the SSPs. The development of the SSPs has led to important methodological improvements and extensions of the present IIASA-ENE modeling tools, including the endogenous representation of land-use change with ESM, which will be critical for future research activities, including the exploration of water and food security issues.

In addition to the SSPs, ENE has been at the forefront of several other community research efforts, including several international model inter-comparison projects that were successfully completed in

2013/2014 (Energy Modeling Forum Study 27, Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates, and Low climate impact scenarios and the implications of required tight emission control strategies). These projects represent multi-year research efforts resulting in a range of robust insights into strategies to address climate change and other energy challenges, and involving over 20 international partners from the integrated assessment and other expert research communities. An important finding from these studies is that a delay of stringent climate action to 2030 must be compensated by much deeper emissions reductions in the medium and long-term if targets like the 2˚C are still to be achieved (see figure below). In terms of impact, the results of above research activities underpin the transformational pathways analysis in the Intergovernmental Panel on Climate Change's Fifth Assessment Report.



Development of greenhouse gas emissions. Current weak climate policies shift deep reductions to later in time, and imply higher risks that low stabilization targets are getting out of reach. (Source: Riahi et al., 2013)

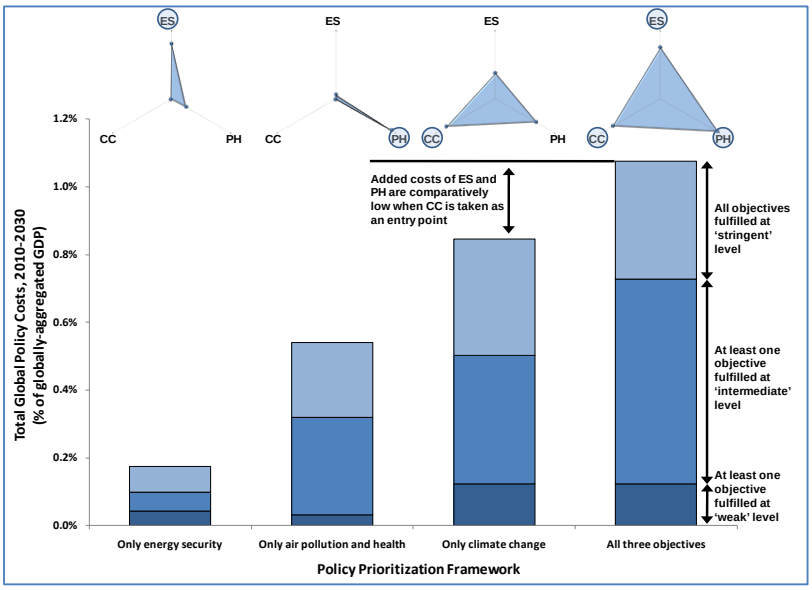
Global Energy Assessment

The Global Energy Assessment (GEA) was a multi-stakeholder initiative that involved over 300 authors and 200 anonymous reviewers and assessed the energy challenges of our rapidly changing world. It identifies 41 comprehensive pathways to resolve the urgent challenges required to achieve a sustainable energy future. Implementation of these strategies relies on strong commitments from policy- and decision-makers to achieve a transformation of the global energy system. Coordinated by the ENE and TNT programs, GEA was led by preeminent energy experts from around the world and is the first ever fully integrated assessment that analyzes energy challenges, opportunities and strategies, for developing,

industrialized and emerging economies. It was supported by government and non-governmental organizations, the UN Organizations, and the private sector.

A major contribution of the GEA scenario analysis to the literature was a broadening of the scope of integrated assessment modeling by simultaneously exploring the relationship between three key energy sustainability objectives: energy security improvement, climate change mitigation, and the reduction of air pollution and its human health impacts (see figure below). The current practice of narrowly focusing on singular policy issues ignores potentially significant synergies, often leading to the implementation of shortsighted solutions that may have unnecessarily costly, long-term consequences.

The GEA report was launched at a high-level side-event during the Rio+20 United Nations Conference on Sustainable Development in Brazil in June 2012. The dissemination effort put a special focus on the developing countries, and in general is ideally placed to support energy initiatives worldwide. It is one of the main scientific supporting documents for the UN Secretary General's Initiative on Sustainable Energy for All.



Costs of achieving societal objectives for energy sustainability under different policy prioritization frameworks. Policy costs represent the net financial requirements (energy-system and pollution-control investments, variable, and operations and maintenance costs) over and above baseline energy-system development. Triangular schematics summarize the performance of scenarios that achieve 'stringent' fulfillment only for the objective(s) targeted under the corresponding policy frameworks (axis values normalized from 0 to 1 based on the full range of scenario ensemble outcomes; CC = Climate Change, ES = Energy Security, PH = Air Pollution and Health). (Source: McCollum et al., 2011)

5. Evolution and Ecology Program (EEP)

Developing new methods and pioneering their applications, EEP analyzes and forecasts how ecological and evolutionary dynamics shape populations, communities, and ecosystems, and how behavioral adaptations, incentives, and regulations determine the fate of groups of interacting agents.

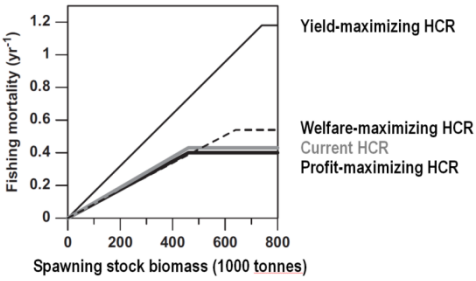
Modern approaches to describing complex adaptive systems need to account for nonlinear feedback, non-equilibrium dynamics, discontinuities and break points, collective phenomena, systemic transitions, behavioral dynamics, as well as multi-level and multi-scale interactions among processes and agents. Ecology is the quintessential systems science, dealing with such challenges in a holistic way. This approach is complemented by studies of adaptation and evolution, to account for the ubiquitous capacity of agents to alter their features and interactions in response to environmental change. Furthermore, applied mathematics and theoretical physics contribute advanced tools to the diverse mix of methods that is characteristic of EEP's research. On this basis, EEP is building bridges between fundamental and policy-oriented, theoretical and empirical, biological and mathematical, and analytical and computational approaches to the systems analysis of the living world.

EEP focuses on three broad areas of research in which the stewardship of our shared natural environment depends on understanding complex adaptive systems involving biological agents and human stakeholders:

- *Fisheries*. Accounting for overlooked adaptations and socioeconomic interactions in the acquisition of living aquatic food resources, two projects investigate *Evolutionarily sustainable consumption* and the *Integrated assessment of fishery systems*.
- *Biodiversity*. Elucidating the formation, maintenance, and loss of biological diversity, the project *Eco-evolutionary dynamics of living systems: theory and applications* and the crosscutting initiative *Evolutionary vegetation modeling and management* examine the complex eco-evolutionary processes underlying biodiversity dynamics in ecosystems.
- *Cooperation*. Recognizing the universal structure of problems and solutions associated with the overexploitation of common goods, EEP analyzes the *Evolution of cooperation* in self-organizing groups, with the new crosscutting project *Equitable governance of common goods* addressing the associated governance challenges.

These studies are complemented by the new cross-cutting project *Systemic risk and network dynamics*, which seeks to demonstrate the integrative power of the emerging field of network analysis by developing a suite of associated tools and applications.

Integrative bio-socioeconomic assessment of harvest-control rules



Comparison of four management policies for fishing Northeast Arctic cod, determining the allowable fishing mortality in a year depending on the stock's total biomass of adult fish estimated for that year.

Eikeset *et al*. (2013) assessed the harvest-control rule (HCR) established by the Norwegian and Russian governments for Northeast Arctic cod, one of the most valuable European fish stocks. The study's findings turned out to be surprising:

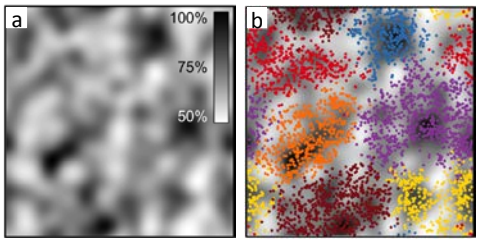
(1) The current harvest-control rule (HCR) is indicated in gray, and turns out to be very similar to the HCR that optimizes the fishing industry's profit, even though fisheries managers have responsibilities to society at large, and not to the fishing industry alone.

(2) Contradicting expectations commonly held among scientists and in the public, the profit-maximizing HCR is more precautionary than the current HCR, yield-maximizing HCR, and welfare-maximizing HCR.

(3) The welfare-maximizing HCR allows higher quotas than the profit-maximizing HCR.

(4) Exploitation under the yield-maximizing HCR turns out to be aggressive, and would take the stock to such low levels that its robustness to environmental fluctuations could no longer be ensured. This finding starkly contrasts with the widely trusted assumption, underlying the current wave of revising fishing policies around the globe, that maximizing sustainable yield is guaranteeing sustainable consumption.

A New Understanding of Biodiversity



Even small amounts of spatial environmental heterogeneity (grayscales in a) suffice to guarantee the long-term coexistence of a diverse set of ecologically equivalent species (with individuals of different species depicted by differently colored dots in b), provided females have a sufficiently strong and costly preference for mating with similar males.

Elucidating the interplay between spatial structure and eco-evolutionary dynamics is a challenge at the forefront of ecosystem research. Running counter to mainstream belief and textbook coverage, M'Gonigle *et al*. (2012) demonstrated the possibility of long-term coexistence of species despite their ecological equivalence. This finding has wide-ranging implications for understanding the origin, maintenance, and loss of biodiversity. As a new explanation of biodiversity, it also helps understand why the plethora of ecological differentiations among locally coexisting species, previously alleged to be necessary, have been so difficult to identify in nature. Regarding ecosystem preservation, the results encourage widening the intervention spectrum from preserving ecological niches to preserving mating processes.

Systems approaches

EEP and its collaborative network have been at the forefront of a variety of methodological innovations, a few of which are highlighted below.

Fisheries

- EEP has been the key driver of the specification of *evolutionary impact assessments* (EvoIAs). Supporting the ecosystem approach to fisheries management, EvoIAs enable structured evaluations of the evolutionary consequences of fishing and allow assessing the merits of alternative management options. In this way, EvoIAs are helping to address a blind spot in contemporary fisheries management.
- EEP has developed a new toolbox for modeling evolutionary dynamics in real-world populations. While earlier process-based models of natural evolutionary dynamics often remained stylized and could not easily be aligned with empirical data, the newly introduced class of so-called *eco-genetic models* enables predictions of how, and how fast, realistically structured populations adapt to environmental changes.

Biodiversity

- *Adaptive dynamics theory* has been one of EEP's key contributions to evolutionary theory and modeling. Adaptive dynamics models arguably offer the best currently available tools for assessing the complex interplay of ecological, evolutionary, and environmental dynamics, accounting for realistic feedbacks driving adaptations in natural and social environments.
- EEP has been at the forefront of developing innovative methods for modeling the eco-evolutionary dynamics of larger communities. Whereas earlier models had to make ad-hoc assumptions about species pools or functional types, methods of *evolutionary community assembly* devised by EEP enable full consistency between the ecological and evolutionary dynamics among large collections of species.

Cooperation

- Overcoming classical game theory's focus on pairwise exchanges, several EEP studies have investigated the *design of institutions and incentives*.
- Moving beyond this simplifying assumption of traditional game theoretical approaches, EEP's research has addressed the consequences of *wealth inequality* among agents for boosting or curtailing cooperation.

6. Risk and Resilience Program (RISK)

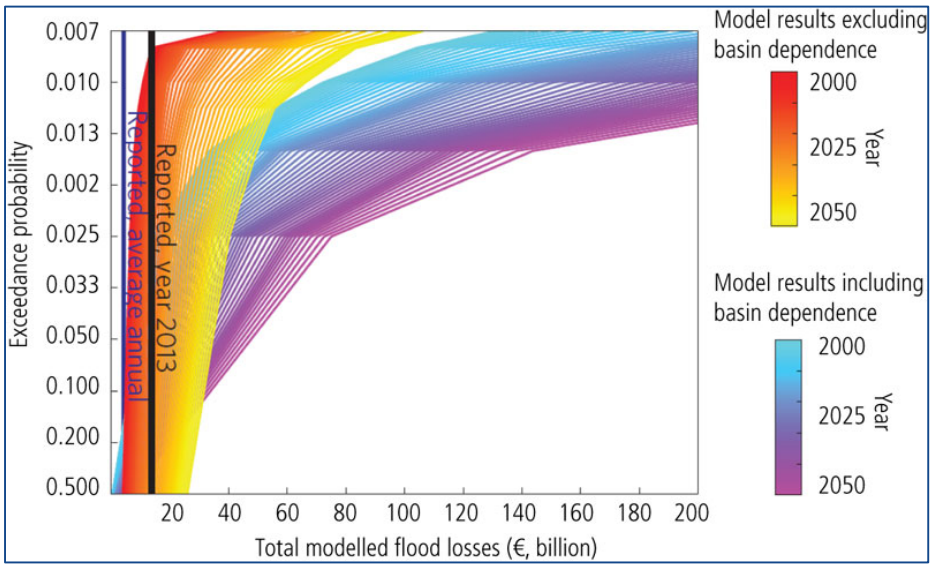
RISK examines environmental and socioeconomic risks with the aim of providing an analytical foundation for the management and governance of natural disasters, addressing climate change, and easing the technological and ecological transitions to sustainability. RISK is organized around five research themes:

- *Risk Analysis and Modeling* develops and applies novel methodologies to assess risks arising in socioeconomic-ecological systems.
- *Understanding disaster resilience* links agendas on sustainable development, disaster risk management, and climate change adaptation.
- *Socioeconomics of risk management and climate adaptation* is concerned with the significant knowledge gaps regarding comprehensive risk management interventions in terms of their efficiency, effectiveness, equity and acceptability.

- *Risk Pooling and Sharing* examines disaster risk insurance and other financing mechanisms with special emphases on how they distribute the disaster burden and provide incentives to reduce disaster impacts.
- *Governance in Transition* analyzes how governance structures shape policy outcomes by contributing to research on decision-making processes, public acceptance, risk perception, cognitive biases, and cultural perspectives, as well as participatory governance design.

Estimating flood risk in Europe

A letter in *Nature Climate Change* (Jongman *et al*., 2014) showed that losses from extreme floods in Europe could more than double (to over €23.5 billion) by 2050 due to climate change and socioeconomic developments. The underlying methodology was innovative in that, for the first time, flood loss estimates accounted for the correlation between river basins. The flow dynamics of European rivers are closely correlated, and are rising and falling in response to large-scale atmospheric patterns that bring rains and dry spells to large regions.



Probabilistic projections of flood losses with and without considering basin dependence. (Source: Jongman *et al*., 2014)

The research shows that the European Commission should be prepared for increased stress on the EU Solidarity Fund (EUSF), and RISK subsequently presented testimony based on this research at an EC public hearing on the topic. On-going research shows that the EUSF falls short of its proclaimed solidarity and it might consider re-orienting to a backup fund for national insurance systems (e.g., for Flood Re in the UK).

Flood resilience

The Flood Resilience Project led by RISK recently received *UNFCCC's Momentum for Change - Lighthouse Award*. This multi-year initiative (sponsored by Zurich Insurance) aims to measure and build the resilience of communities in Mexico, Nepal, Indonesia, and Peru to floods—the most devastating natural hazard globally. In partnership with the Wharton Risk Management Center, the research brings together IIASA's expertise on risk modeling and systems science with on-the-ground activities of the UK development NGO,

Practical Action, and the International Federation of Red Cross and Red Crescent Societies (IFRC). This award provides a public platform to disseminate transformational climate-related actions, which are already making a difference on the ground. Specifically, the project currently studies the potential for interventions to help manage increasing flood risk that emanates from non-resilient urban-rural linkages around the city of Lima, Peru.

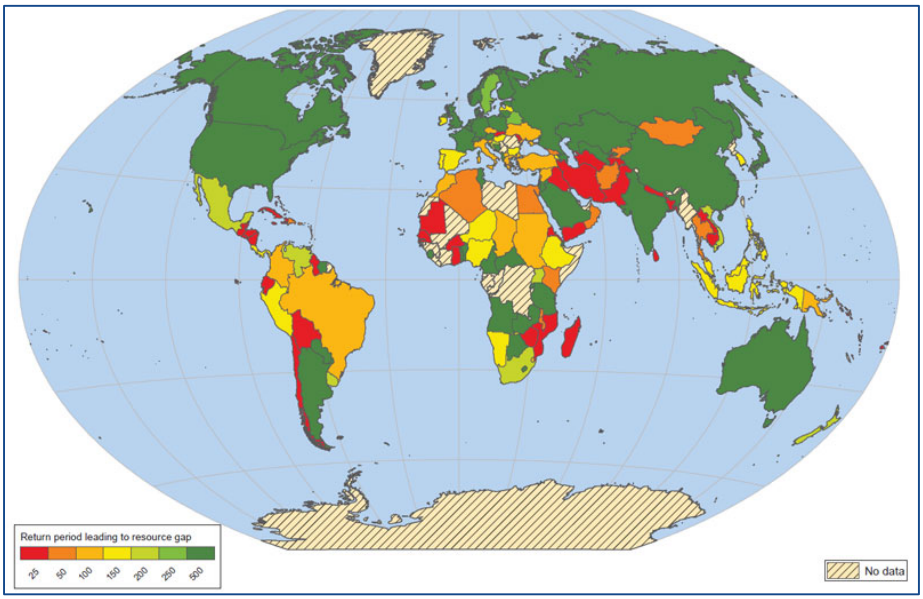
The resilience research builds on RISK's design and implementation of stakeholder participatory processes for managing risks, most recently landslide risk in the Italian town of Nocera Inferiore. The approach respects multiple perspectives on the issue with the aim of crafting an expert-informed compromise (building on research pioneered by UK scientists, Steve Rayner (Oxford) and Michael Thompson (IIASA)). In Nocera Inferiore the participants in the three-year deliberative process reached a compromise on structural and natural engineering measures to stabilize the dangerous slopes above their town (Scolobig *et al.*, 2014).

Catastrophe simulation

Combining natural system information (probability and intensity of natural hazards) with data on exposed and vulnerable populations and assets, RISK's catastrophe simulation model (CATSIM) dynamically and stochastically assesses disaster risks and their fiscal and economic consequences. A recent worldwide application (Hochrainer-Stigler *et al.*, 2014) found that many countries are at high risk (countries colored red in the figure below) of not having sufficient capital to repair critical infrastructure and otherwise respond to extreme events, resulting in serious follow-on consequences for development. Based on CATSIM, RISK has advised a set of developing country governments on financing options for managing their risks.

RISK has also estimated the funding requirements for a global (climate adaptation) fund that would cover high-level risk for the most vulnerable countries (surprisingly, less than €10 billion), - estimates that will continue to inform the climate negotiations. RISK is collaborating with other researchers (e.g., UK scientist, Swenja Surminski (LSE)) on using this research to inform negotiations on the UNFCCC "Loss and Damage Mechanism".

Finally, building on CATSIM, RISK (with EEP and ASA) is examining the systemic risks of natural disasters on financial system stability. The approach is novel, bringing together expertise on non-linear stochastic dependency (copulas) and agent-based modeling.



Global map exhibiting fiscal vulnerability in terms of critical return period event that leads to fiscal stress. (Source: Hochrainer-Stigler *et al*., 2014)

7. Transitions to New Technologies Program (TNT)

The strategic goal of TNT is to further the understanding of the patterns, dynamics, and constraints of technological change, and its drivers and impacts, particularly in areas key for framing global sustainability conditions.

TNT's research aims to improve the empirical understanding that feeds into new modeling approaches of technological change as input to national and international studies and policy processes. The emphasis is on the treatment of technological uncertainty, spatial and actor heterogeneity, and assessments of the potential economic and societal impacts of the pervasive diffusion and adoption of new technologies and techno-economic systems.

TNT's strategic research goal is to focus on the systemic aspects because technological change arises from the spatial and temporal diffusion of individual innovations all the way to the emergence of new technological combinations that could fundamentally redefine products, services, and even entire markets. Consequently, the Program aims to understand the evolution of entire technology systems and not simply that of individual technologies. It draws on empirical case studies, associated meta-analyses, novel technology modeling approaches, and scenario studies including robustness analysis to inform technology policy choices from a systemic perspective. TNT also serves the scientific community at large through software development for scientific data assessments, documentation and dissemination.

An important objective of TNT is to disseminate policy-relevant research findings through global forums and major international scientific assessments. These include, most notably, the Intergovernmental Panel on Climate Change (IPCC), the Global Energy Assessment (GEA), the International Council for Science (ICSU) and the Future Earth initiative, the Sustainable Development Solutions Network (SDSN),

Sustainable Energy For All (SE4ALL), Global Carbon Project (GCP), German Government's Advisory Council on Global Change (WBGU) and other strategically chosen private and public initiatives.

Scientific foundations for understanding technological change

An elucidation of the early or so-called formative or introductory phases of technologies through empirical research provides an opportunity to study fundamental processes of technology evolution that are associated with deep uncertainties. The formative phase not only allows for extensive experimentation with new technological configurations but also for preserving technological diversity and avoiding premature "lock ins". It is also provides an opportunity window for mobilizing new actor networks.

Agent-based modeling of technological complexity and evolution has become an important stream of TNT research. A number of new models with explicit treatment of technology components as well as entire technology systems have been developed and massive numerical simulations have been performed. The results obtained suggest that the evolution of technological complexity is largely scale invariant, that is, unaffected by the level of disaggregation by which technologies are represented in the model. These theoretical results hold important implications for an improved understanding of the rates by which technology systems can change and be modified, as well as for technology risk analyses.

Modeling technological systems

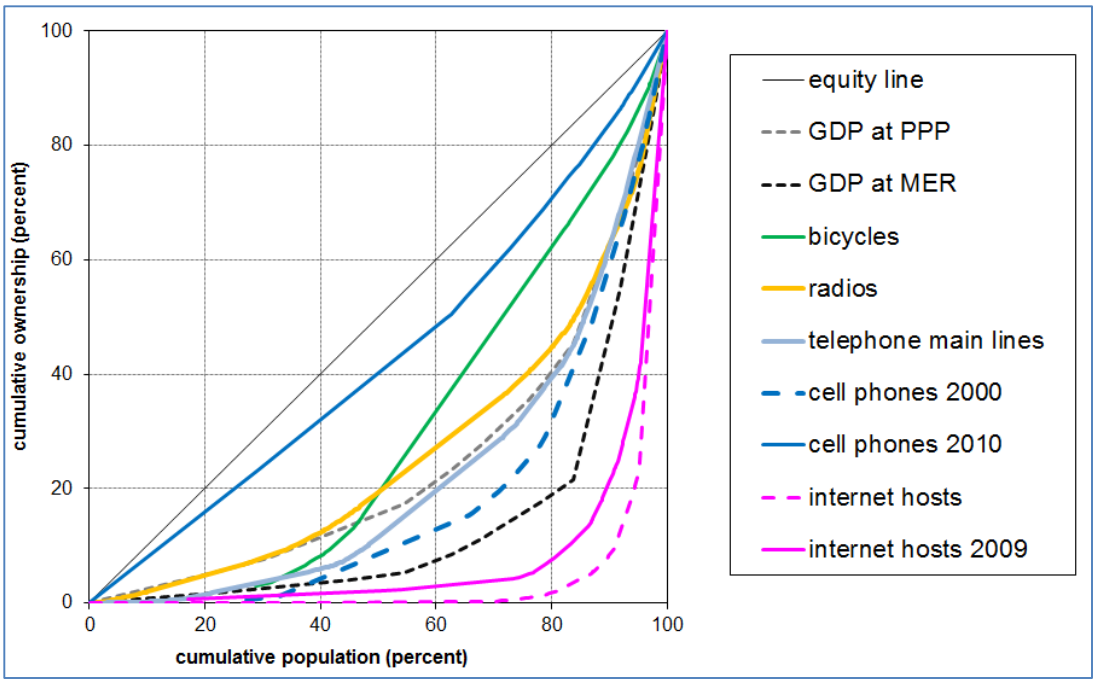
Technology scaling from individual applications all the way to scale of whole industries is an important part of the TNT research portfolio. In collaboration with the Energy (ENE) Program and the Potsdam Institute for Climate Impact research (PIK), Germany, TNT applied new technology scaling methodology for evaluating the plausibility and likelihood of stringent climate policy scenarios in terms of their implied up-scaling dynamics for climate friendly. Collaboration with ENE and researchers from the Research Institute of Innovative Technology for the Earth (RITE), Japan, also continued on improving Integrated Assessment Models in terms of their representation of technology diffusion, and mechanisms of technology improvement including scaling and learning-by-doing. Further model development also aimed at including knowledge and technology spillover effects in a simplified Integrated Assessment model.

Global Energy Assessment (GEA) and Sustainable Energy For All (SE4All)

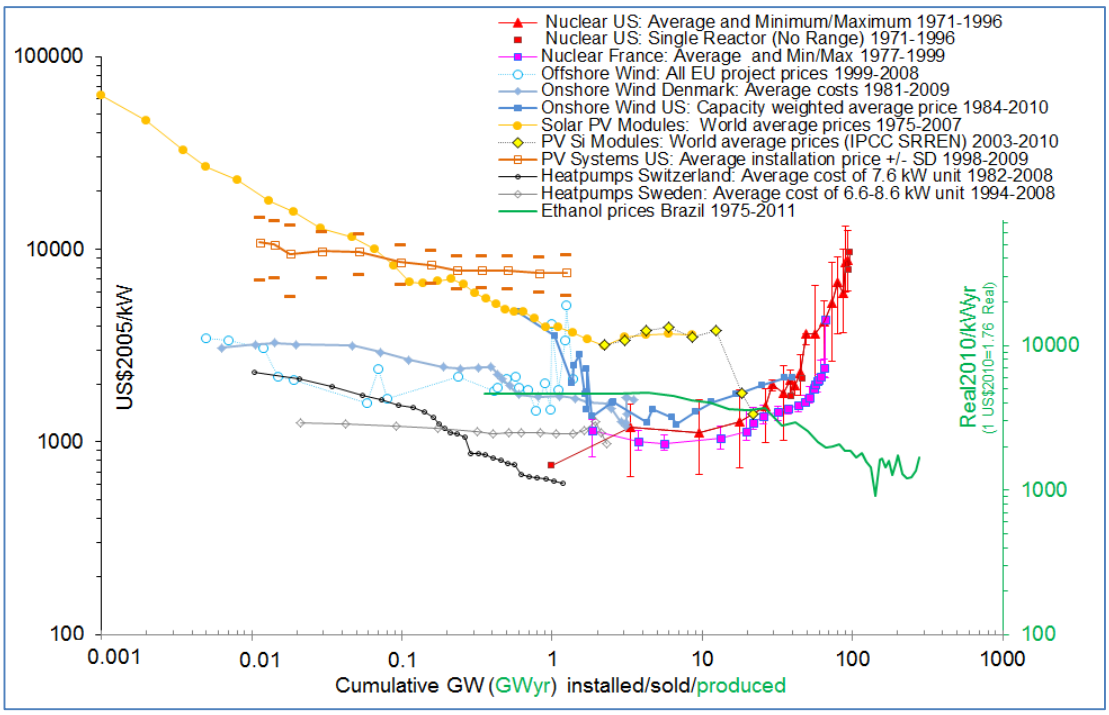
SE4All is a major UN initiative that aims to provide three energy-related global development goals and to translate those into national action plans. The goals include universal access to modern energy, doubling energy efficiency improvement rates, and doubling the share of renewable energy in the final global energy mix – all to be reached by 2030. TNT contributed toward the design and implementation of the national frameworks for action and the work of various preparatory working groups that underpin SE4All. Much of the scientific underpinning was based on the GEA, coordinated by TNT and IIASA that included 300 leading energy experts, and analyzed possible transformations toward sustainable energy futures. Specific research contributions within SE4All include methodological frameworks and policy advice on technology strategies and roadmaps, urbanization patterns as well as national-scale policy modeling embedding within a consistent global and regional modeling framework (model "downscaling"). The value of IIASA's analytical perspective and potential contribution to SE4All has been demonstrated in a recent

paper in *Nature Climate Change* that identified significant climate protection co-benefits of the SE4All development goals.

TNT also provided five authors and a review editor of the Fifth Assessment Report of Intergovernmental Panel on Climate Change on drivers of change, pathways, settlements and urbanization as well as the Summary for Policymakers and the Synthesis report.



Lorenz distribution curves indicating the distribution of technologies across the global population compared with per-captia gross world economic product (GDP) measured at market exchange rates and purchasing power parities. Most equitable distribution is shown as a 45o line. Mobile phones are close to being equally distributed, namely that almost every person has one, while the internet access is most unequally distributed compared to other technologies indicating that the "digital" divide is real.



Learning or experience curves for a number of energy technologies. Shown are capital costs on the vertical axis against cumulative installations on the horizontal (on a double-log scale). Many of the technologies, like the photovoltaic solar portray 30% cost reduction per doubling of cumulative installed capacities. Some technologies like nuclear in France and the US indicate cost increases with increasing installations.

8. Water Program (WAT)

The objectives of WAT are to compile, consolidate and enhance knowledge of global water supply and demand balances, to advance the incorporation of hydrology and hydrologic uncertainty into integrated assessment modeling efforts and scenario development, and to provide a sound scientific basis for responding to current and future global water challenges. In this way the program assesses the robustness of proposed solutions, throughout various water-related sectors and management scales, against a range of possible future socioeconomic changes and technological innovations, in the context of global environmental challenges.

IIASA has been continually been active in water science, as evidenced by the institute's recent prominent roles in several large integrated water projects such as WATCH (Water and Global Change, http://www.eu-watch.org/) and SCENES (Scenarios for Europe and Neighbouring States), in which IIASA worked with many partners, including UK partners CEH Wallingford, the MET office, Oxford University, and the Institute for European Environmental Policy. Because of the complexity of modeling and assessing water fluxes globally, water-related interactions and feedbacks with climate, land-use, energy, and other socioeconomic systems have often been ignored in integrated modeling assessments. However, with water increasingly becoming a globally scarce good, assessments of the trade-offs and synergies among management options that help to ensure joint water, food, energy, and environmental security is urgently needed, and WAT is establishing a critical mass of water knowledge at IIASA to advance the incorporation of water science into nexus assessment and planning studies, and the corresponding tools. For example a

recent paper in *Nature Climate Change* highlighted the vulnerability of European and US electricity supply on the growing scarcity of water for cooling (van Vliet *et al.,* 2012).

Activities

The WAT program was established in conjunction with a flagship project, the Water Futures and Solutions Initiative (WFaS), launched with a high level meeting at IIASA in 2013 which brought together representatives from private industry, government, academia, and nongovernmental organizations. Initial launch partners included UN Water/ UN Organization for Education, Science and Culture, the World Water Council, The International Water Association, and the Ministry of Land, Infrastructure, and Transport of the Republic of Korea, and the consortium around the WFaS Initiative continues to grow, with currently more than thirty organizations represented in project team meetings and official recognition of the initiative as a project of UN Water, a partner in the US Water Partnership, and a member of several other ongoing water initiatives.

WFaS forms the core of WAT's research. It is a cross-sector, collaborative global initiative which develops the scientific evidence and applies systems analysis to help identify water-related policies and management practices that work together consistently across scales and sectors to improve human wellbeing through water security (Kabat, 2013). A stakeholder informed, scenario-based assessment of water resources and water demand, consistent with IIASA work on the shared socioeconomic pathways for the Intergovernmental Panel on Climate Change and employing ensembles of state-of-the-art socioeconomic and hydrological models, test the feasibility, sustainability, and robustness of options that can be implemented today and can be sustainable and robust across a range of possible futures and associated uncertainties we face. The WFaS Initiative includes case studies to zoom in on particular issues and regions, and knowledge sharing networks to share policy, management, and technical solutions that have been effective in the bio-physical and socioeconomic contexts to which they have been applied, so they can be assessed for application in similar conditions in other regions. A few examples of case studies within the WAT program for WFaS include:

- *Sustaining and Improving Rural Livelihoods through Adaptive Approaches*, which clusters studies in three geo-graphically distinct regions in India to assess, with communities, adaptive approaches to sustaining and improving rural livelihoods through joint land, soil nutrient, and water management.
- *Sustainable solutions against groundwater salinization in Coastal Areas***,** a project under development as part of USAID's Securing Water for Food Initiative, in which IIASA works with the engineering company ARCADIS to pilot technology for conjunctive management of freshwater and saltwater in coastal aquifers to augment water supply, and assess the biophysical and socioeconomic conditions under which the technology can be effective and robust.
- *Integrated analysis of climate change, land-use, energy and water strategies*, a collaborative case study that preceded the launch of WFaS, but reinforced the need for integrated planning across climate, land, energy, and water and across management scales, by showing that local,

single-sector planning can result in the opposite of the intended outcome, but when all sectors are considered, a synergistic, adaptive solution can be found.

Case studies such as these advance assessment methodologies for specific topics, involve local stakeholders to develop local and regional scenarios consistent with the global scenarios, and develop tools to assess and classify management options that are effective under various local conditions. Knowledge gained in the case studies provides vital information and feedback to the global scenario development and options analysis, while the global analysis provides the macro-scale conditions under which local planners must work.

Although WAT and WFaS are still in their infancy, WFaS team members have organized seven international events, given more than 50 conference presentations, been members of global task forces on water issues, such as the GWP-OECD Task Force on Water Security and Sustainable Growth and the Scientific Programme Committee for Stockholm World Water Week, and updated knowledge and decision support tools like the GAEZv4 web portal, which focuses on the food water nexus. These have been important steps in building capacity and networks, in order for WFaS to help efforts to reach international consensus around resource management strategies that ensure enhancement of human wellbeing and are effective, sustainable, and robust across the uncertain futures we face.

9. World Population Program (POP)

POP addresses the human development dimension of global change. It comprehensively studies the changing size and composition of human populations around the world and analyzes both their impacts and the differential vulnerabilities by age, gender, and level of education.

Over the past years, POP has spearheaded several methodological innovations that have significant impact for our understanding of contemporary global challenges. These range from the development of the first probabilistic population projections to work on redefining age and aging, as well as innovative analysis of demographic aspects of cognitive aging, labor force participation and health. The global population projections by age, sex and level of education for 175 countries have just been completed and are available on the Internet. POP also regularly produces demographic data sheets that make these newest research findings accessible to a broad public.

POP is also a world leader in the analysis of population and environment interactions and, in particular, in developing scenarios on population and climate change in the context of IPPC. POP also greatly benefits from synergies within the Wittgenstein Centre for Demography and Global Human Capital where IIASA is one of three founding institutions together with the Austrian Academy of Sciences and the Vienna University of Economics and Business, as well as through a global network of collaborating regional population centers and scientists from IIASA member countries.

World population projections and human capital

Based on the methodological foundation of multi-dimensional mathematical demography developed at IIASA in the early years of the demography group, POP recently published a landmark study summarizing the state of the art about the drivers of future fertility, mortality, migration and education trends and

producing global population scenarios by age, gender and level of education for all countries. They are based on the input of over 550 international population experts assessing the validity of alternative arguments important for future trends and which were synthesized in meta-expert meetings on five continents.

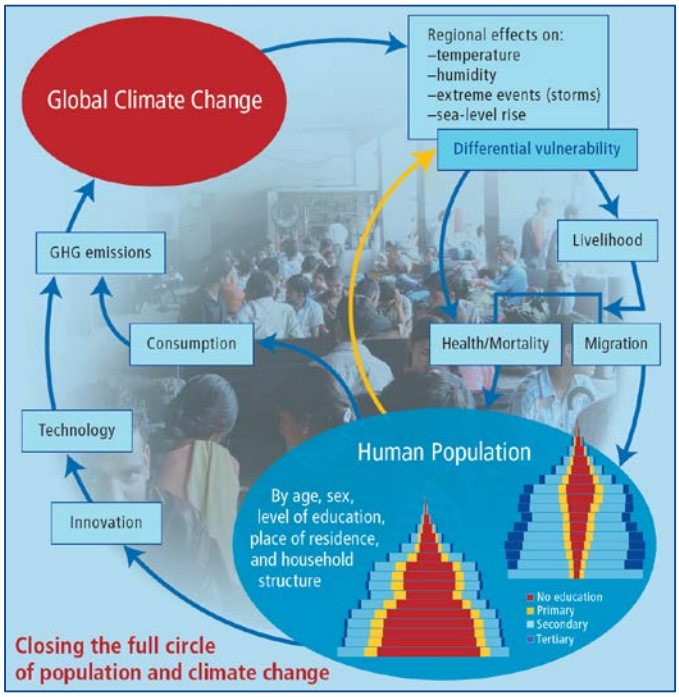
This process of producing a new set of world population projections went in tandem with the definition of the next generation of Intergovernmental Panel on Climate Change related scenarios that should capture both the socioeconomic challenges to climate change mitigation and adaptation. The demographic part of these 'Shared Socioeconomic Pathways' (SSPs) scenarios was produced by POP in collaboration with other Wittgenstein Centre demographers.

All the described work is comprehensively documented in an Oxford University Press book entitled *World Population and Human Capital in the 21st Century* (Lutz *et al*., 2014). Selected results for all countries are presented in a numerical appendix. Highlights are included in an Executive Summary and the complete results are presented on a designated web site www.wittgensteincentre.org/dataexplorer/.

Population policies in the 21st century

POP's research has also led to a new priority focus for population policies in 21st Century: education and health, particularly of women. Explicitly addressing education gives new insights about what is the socially optimal fertility level, as well as what are the drivers of the 'demographic dividend' and 'unmet need' for family planning. POP Director Wolfgang Lutz highlights this new population policy paradigm in a recent paper in *Population and Development Review* (Lutz 2014). A policy brief summarizing the key points was also distributed to the participants of the Special Session of the United Nations General Assembly to review the International Conference on Population and Development (ICPD) Program of Action (22 September 1014, New York), which has set the agenda on global population policy beyond 2014.

Population, development and climate interactions



This figure produced by POP depicts how the interactions between population change and climate change can be conceptualized. While in an earlier POP book on *Population and Climate Change* the focus was more on the effects of population changes on GHG emissions, more recently POP has been studying the vulnerability and adaptation side of coping with unavoidable climate change (Ecology and Society, March 2014). This was also the topic of a recently completed ERC Advanced Grant to Lutz.

Over the past two decades POP has carried out a number of in-depth case studies on Population-Development-Environment (PDE) interactions that use the tools of systems modeling to assess the interconnection of these different aspects in determining future human wellbeing. Recently a new proposal has been submitted to the ERC under the title of "Population Based Sustainability Science". Here the goal is to use systems models to assess the future trends of an indicator of human wellbeing called "Empowered Life Years" which should not decline over time as a sustainability criterion.

A more specific example of cross-program systems analysis is the work carried out jointly by POP and AIR scientists on a Simple Economic Demographic Interaction Model (SEDIM) to study how alternative policies for air pollution abatement affect wellbeing of India population. The study published in the journal *Environmental Science and Technology* (Sanderson *et al.*, 2013) examines interplay between population, economic and ecological factors and assess direct and indirect costs of the additional pollution control measures (extra budgetary expenditures versus increased productivity due to the reduced morbidity).

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