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Creating a Climate-Friendly Sustainable Energy Future: The Role of Mathematics

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Introduction: Why energy is so important for sustainable development

In October 2012, Hurricane Sandy swept across the North-Eastern coast of the United States and left 60 million people in the dark lacking power, heating and communication. For several days that followed schools, subways, airports were shut down. And even the New York Stock Exchange was closed. The economic loss as a result of the Hurricane was estimated to be at least USD 50 billion. Sandy's devastating impact illustrates the vulnerability of humans to natural disasters. But most importantly, it also revealed the urgency to address sustainability challenges in a comprehensive and effective way, no matter where you are in the world. Unsustainable sources of energy are widely acknowledged to be the biggest cause of climate change. There is a growing consensus that climate change has increased the number of incidents of natural disasters in recent years. In the year 2000, energy-related emissions accounted for 74% of the world's greenhouse-gas emissions (Mackay, 2009). Industry alone accounted for one third of these emissions.

On the face of it, the story about energy is about the challenge of exploiting finite natural resources in a sustainable way and avoiding energy intensive, wasteful production and consumption patterns which can have major adverse impacts on the environment. Besides climate change, these impacts also include the threats of acidification, ozone depletion, abiotic resource depletion, acid rain, radiological effects, eco-toxicity and many more. But ultimately this is only one side of the story and the challenge of sustainability.

Fundamentally, the story about energy is also about something else. It is about addressing sustainable development in all of its three dimensions in a balanced and integrated way. Besides the environmental dimension, these include equally important social and economic dimensions. The stark reality is that, in today's world 1.3 billion people still lack access to modern, affordable, reliable energy services. And, 3 billion people rely on traditional biomass for cooking (IEA, 2011). Many of these people are poor and spend significant amounts of their limited income on expensive and unhealthy forms of energy. As a result, 1.5 million people die each year from indoor air pollution. This is estimated to be more than the annual number of people that die from Malaria. Lack of access to modern energy services, therefore, remains a considerable obstacle for people in the developing world to escape the vicious cycle of poverty. They are not only poor but

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they are also energy poor. Very often the burden of energy poverty disproportionately falls on women who spend many hours collecting fire wood from faraway places.

Modern energy systems are central to sustainable human development in all of its three dimensions. Energy has been the driving force of economic development and in improving living standards worldwide. Energy powers productive activities in industry, transport systems and households. Energy improves human well-being because it impacts almost all areas of human life. In the words of the United Nations Secretary-General, “Energy is the golden thread that connects economic growth, social equity, and a climate and environment that enables the world to thrive”. In short, energy is the big integrator. In terms of the present international development agenda, energy is also often said to be the ‘missing Millennium Development Goal’[1]. Sustainable energy for all is a major global challenge.

The world is expected to have a global population of 9 billion people by the year 2050, the majority of which will be in developing countries. This will compound our present problems if we remain on our current development path. Even if technology developments reduce energy intensities, world energy demand is likely to increase in line with fast growing population. Energy, so important for development and human well-being in many ways also presents significant challenges. It is, therefore, essential that we identify and implement sustainable patterns of production and consumption to balance people’s legitimate right to development with the inescapable fact that the Earth has finite resources. Energy efficiency and the integration of renewable sources of energy will play a major role for sustainable development (Maréchal, 2004).

In recognition of these pressing energy challenges, the United Nations Secretary-General recently launched his “Sustainable Energy for All” (SE4All) initiative which features three complementary objectives to be met by the year 2030: ensuring universal access to modern energy services; doubling the global rate of improvement in energy efficiency; and doubling the share of renewable energy in the global energy mix (Holliday and Yumkella, 2012).

The Role of mathematics for achieving the sustainable energy future

Achieving the three SE4All goals through the development of new sustainable energy systems involves many technical challenges in which mathematics plays a crucial role. First, mathematical analysis helps provide clarity in understanding the nature and extent of these challenges. It also allows us to consider the multidimensionality, interlinkages and numerous feedback mechanisms among energy systems. This helps us to minimize risk and provides a rational system approach in making appropriate sustainable energy decisions. Multi-criteria decision analysis (MCDA) methods are increasingly popular in decision-making for sustainable energy. This is because of the multi-

[1] UN Millennium Development Goals (MDGs) – which range from halving extreme poverty to halting the spread of HIV/AIDS and providing universal primary education, all by the target date of 2015 – form a blueprint agreed to by all the world’s countries and leading development institutions. They have galvanized unprecedented efforts to meet the needs of the world’s poorest.

dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems (Kowalski, 2010; Wang, 2009).

Mathematics also helps deliver useful insights on how to achieve a sustainable energy future in a changing and uncertain world. To cope with the complexity and uncertainty of future developments and with the plethora of often contradictory social and political preferences, mathematical models are used to develop different scenarios and bring order to a complex reality. These scenarios provide empirical evidence as well as coherent and credible explanations to describe the different paths that lead to alternative outcomes. On this basis, they allow decision-makers to choose preferred outcomes. Because they involve using multiple perspectives to explore complex problems, scenarios can help us to create a shared understanding of possible developments, options and actions (Davis, 2002). They are also useful to gain public support for particular evidence-based policy decisions.

To expand on this, let us take the recent example of the Global Energy Assessment (GEA, 2012) conducted under the auspices of the International Institute for Applied Systems Analysis. More than 500 scientists and experts world-wide have collaborated to examine scenarios for transforming the future global energy system. In doing so the overarching aim was to assess the technological feasibility and economic implications of simultaneously meeting a range of sustainability objectives, including the objectives of the SE4All initiative. These scenarios provide the basis for effective policy-design and decision-making to transform energy systems.

We can also achieve the transition to a sustainable energy system by reducing energy demand as well as by combining alternative energy resources. But in-depth mathematical modeling, such as sensitivity analysis shows that improving efficiency throughout the energy system is the most important option to achieve the energy transformation toward a more sustainable future.

To address the environmental impact of energy systems, we must consider the entire life cycle of a product or process, from acquisition of energy and material resources to utilization and ultimate disposal. The mathematical tools provided by life cycle assessment (LCA) allows environmental issues to be quantified and related to the specific part of the life cycle that gives rise to them (Rosen, 2009). Life cycle analysis is very useful for comparing the impacts of different activities so that often hard choices can be made. It is also useful in developing a better understanding of the materials and waste products involved with various types of energy technologies. LCAs have been performed for various energy activities, from processes involving natural gas, nuclear power, hydrogen, solar and wind (Rosen, 2009; Solli, 2006). For instance, LCA can be used to evaluate the most energy efficient alternatives by calculating the net energy balance and CO_{2e} footprint when converting cars from petrol to a mixture of petrol and bioethanol produced from corn.

Advances in mathematics and computing power have also helped us design better systems for generating and scaling up renewable energy technologies. But integrating intermittent renewable energies, such as wind and solar power, in the electricity grid can add uncertainty due to weather variability. This makes planning and scheduling more challenging and requires sophisticated mathematical models. Mathematical techniques are critical to integrate renewable energies into the grid from sun tracking simulations to models predicting wind, wave and tidal-currents more accurately (using Navier-Stokes equations and mathematical theories of fluid dynamics).

Resource estimation and predictability is a critical factor in the development of renewable energy technologies. Methods for predicting wind power generation include numeric weather prediction, complex statistical methods, methods based on neural networks and hybrid methods (Gao, 2012). It is also critical for investor confidence to be able to predict device response, performance and survival in energy systems. Mathematics is also essential in the design of modern wind turbine blades and in optimizing wind turbine placement, as well as in the design of solar photovoltaic (PV) systems or concentrated solar power systems. Enhanced geothermal systems will not be built before their design is passed through extensive mathematical modeling (Gerritsen, 2009).

Some limitations of mathematical models and conclusion

Applying mathematics to global energy issues is one of the important building blocks for the development of a sustainable future. Key challenges include harnessing sustainable energy sources and carriers, increasing energy efficiency, reducing environmental impact and improving socioeconomic acceptability. The choices made in selecting pathways towards an energy transition are also inextricably linked to broader international development issues and goals, including the United Nations Millennium Development Goals.

But it is important to be aware that there are limitations to the use of mathematics when applied to the challenges of sustainable development. We have seen that issues related to sustainable development are extremely complex and involve interactions between physical systems, nature, and humans with even more complex feedback mechanisms that are difficult to understand. This is despite the increasing sophistication of scientific, mathematical and econometric modelling and scenario analysis. Two sets of limitations stand out in particular. A first set of limitations is directed at mathematicians and scientists, a second at policy makers applying mathematical models in practice.

First, mathematical models will always tend to simplify our complex reality due to the need for standardization and abstraction. They work on the basis of ‘stylized facts’. As the Austro-British philosopher Karl Popper (1959) reminds us, no matter how good they are, our hypothesis and models can actually never be proven true. We can always falsify them in the event of new knowledge and evidence, but we will never be able verify them definitively. Consider Popper’s famous "black swan" argument which stipulates that no number of statements reporting observations of white swans allows us to derive the universal statement '*all swans are white*'. Reporting one single observation of a black swan can prove our hypotheses and models to be false. In short, mathematical models are limited to the extent that they ultimately build on non-verifiable assumptions. Our statistical models can often only produce corroborative evidence and not absolute proof.

Second, we also need to be aware that in the process of proceeding from the insights of mathematical or statistical models to particular policy decisions, human interpretation and political judgement are necessary. We often have to rely on a balance of probabilities. Our interpretations and judgements cannot, therefore, be separated from the values and belief systems we harbour. This necessarily adds a subjective element to the process of policy making. This subjective element would occur even if we could verify our mathematical hypotheses (which as we just saw is by itself impossible). The problem or limitation we are looking at here is quite similar to the one that has kept generations of philosophers from David Hume (1739) to G.E. Moore (1903) busy, namely how to derive an "ought" (policy or normative decision) from an "is" (a mathematical or positive hypothesis about reality). Put simply, mathematical models are limited to the extent that they are incapable of devising policy decisions by themselves.

At the end of the day, our capacity to employ mathematics in the process of designing a sustainable energy future requires that both scientists and policy makers preserve a degree of humbleness and a good understanding of the complex economic, social, political and institutional context in which decisions have to take place when designing or interpreting mathematical models. Only in this way, can we hope to also find workable solutions to the intricate and difficult challenge of creating a climate-friendly sustainable energy future. But in meeting this challenge, mathematics is a powerful tool.

References

Davis, G., 2002. *Scenarios as a Tool for the 21st Century*, Shell International Limited.

Gao, W. and Liu, Z., 2012. *Wind Power Prediction Using Neural Networks*, Conference Paper, IEEE Energy Conversion Conference and Exposition, National Renewable Energy Laboratory, NREL/CP-5500-55871, August 2012.

GEA, 2012. *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Gerritsen, M., 2009. *Mathematics in Energy Production*, Department of Energy Resources Engineering, Stanford University.

Holliday, C. and Yumkella, K., 2012. *The Secretary-General's High-level Group on Sustainable Energy For All*, United Nations, New York, USA.

Hume, D., 1739. *A treatise of human nature.*

International Energy Agency, 2012. *World Energy Outlook 2012*, OECD Publishing.

Kowalski, K., 2010. Sustainable Energy Transitions in Austria, A Paticipatory Multi-Criteria Appraisal of Scenarios, DPhil., University of Sussex. Available at: http://sro.sussex.ac.uk/

Mackay, David, 2009. *Sustainable Energy - Without the Hot Air*, UIT Cambridge Ltd, Cambridge, England.

Maréchal, F., Favrat, D., Jochem, E., 2005. *Energy in the perspective of the sustainable development : the 2000 W society challenge*, in Conservation & Recycling, vol. 44, num. 3 spec. iss., p. 245-262.

Moore, G.E., 1903. *Principia Ethica*. Cambridge University Press, Cambridge, UK.

Popper, K. 1959. *The logic of scientific discovery*. Basic Books. New York.

Rosen, M., 2009. *Energy Sustainability: A Pragmatic Approach and Illustrations*, Sustainability 2009, 1, 55-80

Solli, C., Stromman, A.H., Hertwich, E.G. *Fission or Fossil: Life Cycle Assessment of Hydrogen Production*. Proceedings of the IEEE 2006, 94/10, 1785-1794.

Wang, J., Jing, Y., Zhang, C., Zhao, J., 2009. *Review on multi-criteria decision analysis aid in sustainable energy decision-making*. Renewable and Sustainable Energy Reviews, Volume 13, Issue 9, December 2009, Pages 2263–2278.