Contrasting different electricity futures by comparing a large number of optimized scenarios

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The consensus in climate policy is that rapid and deep emissions cuts are necessary in order to avoid dangerous climate change, and this implies a decarbonization of most of the energy sector, and in particular, complete decarbonization of electricity production. The structured exploration possible with energy systems models provides crucial analysis for this task; however, it also poses challenges. First, because of the many different technical possibilities and the contested form of the future decarbonized energy system, the ability to explore large numbers of possible scenarios defined by both technical and non-technical constraints is crucial to provide insight into feasible outcomes. Second, existing models struggle with emerging technical challenges, such as the rising importance of flexible demand, distributed generation, and integrating intermittent supply from renewables. Third, the energy debate is fraught with widely diverging interests and positions, so energy policy analysis can be seen as a prime example of post-normal science. Paying particular attention to the process of compiling, documenting and releasing model code and data could provide crucial legitimacy to scientific results in this context. We here present Calliope, a model intended to help address these three challenges. It is designed from the ground up to take advantage of modern software development methods to deal with high resolution, to rapidly set up many runs on a computing cluster in order to explore a range of different scenarios, and it will be released under an open-source license together with extensive tests and documentation.

Calliope represents the electricity sector with abstract nodes that can represent any mix of production, consumption and storage of energy, explicit in time and space (an extension to other energy carriers is planned). Models are defined in a flexible format based primarily on YAML files (a pure-text human-readable structured data format). Due to this design, hundreds or even thousands of runs with the same base model but varying parameters can be defined simply by selecting a parameter and a list of possible values. The resulting model can be offloaded to a supercomputing cluster or run on a regular desktop machine. The abstract nodes framework allows an additional innovation: the use of modular, flexible "resource streams" to provide resource data explicit in space and time. For the example of wind power, the underlying resource is wind speed at different heights, and the resource stream consists of a validated model for wind power that turns a global database of wind speeds into time series of the potential power generation from a wind turbine or wind farm given its size and conversion efficiency. Currently, three resource streams are available: wind power, solar PV power, and solar CSP power. Combining these streams with the Calliope framework's ability to define a node's key parameters in time and space, it is possible to depict current and emerging technologies with the desired degree of detail, and to easily exchange any resource stream for a different one in order to, for example, analyze variations in underlying technology models and data. This allows an unprecedented focus on the contribution of variable renewable energy sources.

We demonstrate the use of the modeling framework with two cases. The first case systematically examines the degree to which concentrating solar power (CSP) plants could be a reliable source of baseload and dispatchable electricity, using their built-in thermal storage capability. Given uncertainty over the availability of economically feasible technologies for power storage, this feature of CSP plants could make them an important component of a clean energy system. We simulate the operation of CSP plant networks in four world regions using hourly weather data. The results show that in the four regions we examine, it is possible to guarantee up to about 50% of peak demand at non-prohibitive costs. Beyond this, regions differ. In the Mediterranean basin and in Southern Africa, CSP plants could provide availability approaching 100% at competitive costs, whereas in the United States and in India, the cost for such high availability is likely prohibitive. We conclude that CSP can play a key role in some parts of the world, but wide geographic coverage and an appropriate mechanism for coordination are essential for it to realize this role.

The second case is an application of the modeling framework to explore different possible futures for the UK electricity system. This case adds additional complexity by depicting parts of the UK electricity system divided into different zones, and the spatial balancing possibility by having renewable energy sources installed in different configurations across these zones. We define three stylized extreme cases: (1) a system based primarily on solar and wind generation, (2) a system based primarily on nuclear generation, and (3) a system based primarily on fossil-fuel powered generation (possibly with carbon capture and storage facilities). By examining a range of scenarios combining these three extreme cases to varying degrees, we can find preferred technology combinations in terms of cost, security of supply, and greenhouse gas abatement potential. We can also examine possible inflection points, for example, how overall levelized electricity cost changes as wind capacity is added and how adding wind capacity in different geographical patterns influences this. We present preliminary results from this case demonstrating the analysis of a large number of scenarios to scrutinize different combinations of technologies.