Embedding the United Nations sustainable development goals into systems analysis – expanding the food-energy-water nexus

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Abstract

Background

There have been many studies that consider the nexus interactions between energy systems, land use, water use and climate adaptation and impacts. These studies have filled a gap in the literature to allow for more effective policymaking by considering the trade-offs between land use, energy infrastructure as well as the use of water for agriculture and providing energy services. Though these studies fill a significant gap in the modelling literature, we argue that more work is needed to effectively consider policy trade-offs between the 17 United Nations Sustainable Development Goals (SDGs) to avoid missing important interactions.

Results

We examine the 17 SDGs to determine if it should be included in a modelling framework and the challenges of doing so. We show that the nexus of climate, land, energy and water needs to be expanded to consider economic well-being of both individuals and the greater economy, health benefits and impacts, as well as land use in terms of both food production and in terms of sustaining ecological diversity and natural capital. Such an expansion will allow systems models to better address the trade-offs and synergies inherent in the SDGs. Luckily, although there are some challenges with expanding the nexus in this way, we feel the challenges are

generally modest and that many model structures can already incorporate many of these factors without significant modification.

Finally, we argue that SDGs 16 and 17 cannot be met without open-source models and open data to allow for transparent analysis that can be used and reused with a low cost of entry for modellers from less well off nations.

Conclusions

To effectively address the SDGs there is a need to expand the common definition of the nexus of climate, land, energy, and water to include the synergies and trade-offs of health impacts, ecological diversity and the system requirements for human and environmental well-being. In most cases, expanding models to be able to incorporate these factors will be relatively straight forward, but open models and analysis are needed to fully support the SDGs.

Keywords

Energy modelling; UN Sustainable Development Goals; Food-water-energy nexus; Sustainability; Policy

Highlights

- Nexus modelling needs to be expanded to address the United Nations sustainable development goals.
- Human well-being, health, ecological diversity, and natural capital all need to be included in nexus analysis
- Sustainable Development Goals 16 and 17 require open source models and open data to empower development

Introduction

The United Nations Sustainable Development Goals (SDGs), adopted by the UN in 2015, provide a roadmap for 17 areas of focus for international development [1]. The SDGs can be applied both by countries to track and address internal development goals, and by the UN and other agencies to direct development funds. One challenge that becomes apparent after even a cursory examination of the SDGs is that each goal is inextricably linked to many of the other goals. For example, goal 2: zero hunger can likely not be met without addressing goal 1: no poverty, and vice versa. As another example, McCollum et al. [2] provide an analysis of the interactions between goal 7: clean and affordable energy and each of the other goals and find that essentially every goal has at least some interaction with goal 7.

At the same time, systems modellers have begun to recognize the interactions between different sectors, what many refer to as modelling the 'nexus'. Recent work has begun to incorporate energy planning with land and water use planning to address the 'nexus' between these different sectors and their climate and environmental impacts. This shift has occurred to enable the analysis of land and water implications of different energy sources including bioenergy and renewable sources that have different environmental impacts than traditional fossil sources. These integrated modelling frameworks address some of the interactions between these sectors and allow for more effective decision making. As an example, a nexus modelling study for the city of New York found that many energy-saving strategies increased water use and vice versa [3]. Only by studying the interactions between the different nexus aspects can these trade-offs, as well as potential synergies, be effectively identified, addressed, and mitigated.

Though the systems modelling literature to date has contributed to addressing the trade-offs at the nexus of land, water, energy and climate we argue that there is a need to consider other socio-environmental trade-offs than have been, to date, incorporated into such models. Specifically, we argue that there is scope to incorporate many different aspects of the SDGs into systems models and to thereby identify both trade-offs between policies and also identify beneficial synergies. Such a structured approach to incorporating different aspects of the SDGs into systems modelling would contribute to better policy-making.

In this paper we review each of the 17 SDGs and identify specific linkages of each to systems modelling and specifically, the integration of the SDGs into either techno-economic capacity optimization models or energy-economy type models. In many cases specific connections between the SDG and these existing system models can be identified. In this case, we attempt to describe the specific linkage that could be incorporated into the model framework. In other cases, the links are more conceptual and only general principles are identified. This builds on the work by McCollum et al. [2] who identify specific linkages between goal 7, clean and affordable energy, and each of the other goals but, in this paper, we focus on the ability to incorporate aspects of each goal into systems models rather than the linkages between the goals.

We start this paper with a short overview of the existing system models and paradigms that have been applied to addressing some of the interactions envisioned by the SDGs. We then review each of the 17 SDGs and discuss how or if each goal can be incorporated into systems models. We summarize these discussions in an overview table that identifies two aspects of each goal: the importance of including aspects of this goal in systems models and the ease with which these aspects can be modelled.

Recent Modelling Advances

In a very broad sense, there are two distinct modelling paradigms at play in the literature when addressing development and the SDGs. The social sciences/economists usually apply whole economy models such as Computable General Equilibrium (CGE) models. These models incorporate elasticities of substitution between different economic sectors to determine broad stroke, big picture impacts of different policy decisions. They also, through these elasticities, include the impacts of individuals and individual preferences for certain products over others. Such models are often used to analyse economy-wide policies such as the imposition of a carbon tax on general economic growth and overall welfare. The engineers, on the other hand, generally apply technologically explicit and detailed models to determine system operation and optimal system build-out. These optimization type models generally contain much more detail about specific technologies, incorporating specific power generation technologies, specifics about available resources, etc. They are used to determine system expansion plans, system operation and other such engineering decisions and can model the impacts of very specific policy decisions such as renewable portfolio standards, and can be broadly classified as either long-term capacity expansion models or economic dispatch models depending on the temporal resolution considered. The trade-off with optimization models is that they generally cannot include the substitution elasticities and price changes of CGE models. Although some hybrid model structures have been developed over time, these two general modelling paradigms are still the main systems modelling tools in the literature.

Recent modelling advances have worked to expand these modelling paradigms to include more integrated aspects of these different model structures. Two general approaches have been used: 1. incorporating more details into a single model structure; and 2. coupling models of different sectors and/or different temporal and spatial resolution by either soft or hard linking.

Models that have incorporated more details into a single model include the Climate, Land, Energy and Water systems (CLEWs) modelling framework [4], [5] and the NExus Solutions Tool (NEST) framework [6], [7]. A CLEWs study for the city of New York found that decisions to increase energy efficiency, in some cases, increased water use and that decisions not considering these interactions led to inefficient use of resources [3]. Without the CLEWs analysis these trade-offs would not have been clear and inefficient use of resources would have resulted. When the NEST framework was applied to the Indus River basin in Asia it showed that the interlinkages between water and energy have significant policy implications [8]. Both the CLEWs and NEST frameworks are optimization models that choose the optimal development path within the constraints and trade-offs defined in the model structure, and both focus solely on the climate, land, water and energy nexus.

The second approach, of coupling models of different sectors and/or different temporal/spatial resolution, is the approach taken by Deane and Brinkerink out of UCC [9]. They combine two modelling frameworks into a combined model. At a high level, the global CGE type model GCAM [10] is used to develop demand profiles based on broad policy decisions. The GCAM outputs are used to drive the capacity expansion and operational model developed in PLEXOS [11]. Although the work is not yet published, they are showing how interactions between the different sectors at a global scale can drive power system operations at the hourly scale [9]. In a similar vein Bieber et al. [12] present a model of an urban energy system combined with an agent-based model to evaluate the impacts of climate change on the provision of energy and water in Ghana and find that combining these models highlights the vulnerability of the power sector and the need for diversification. García-Gusano [13] links a life cycle assessment model to a power system planning model to incorporate the life cycle impacts of the power sector into a capacity expansion model. They find that including LCA indicators in long term optimization models enhances the policy insights gained from such models.

Focussed only on the power sector, Zhang et al. [14] present a model that integrates a multi-objective, long term capacity expansion optimization model with an hour-by-hour operational simulation model to enhance policy relevance. They find that the model is able to show the trade-offs between nuclear energy and variable renewable energy that could not be evaluated with either model alone. Deane et al. [15] used a similar approach to connect an Irish energy system model with an Irish power system model for a specific year. They find that the combined model significantly improves predictions of CO_2 emissions and the costs of proposed scenarios in both models. Cuesta et al. [16] present a framework for inclusion of social indicators in a systems model for small communities. They find that the inclusion of social indicators provides advantages to the optimization paradigm and provide guidelines for modellers to select the best tools to do so.

Overall, each of these modelling paradigms and each combined model works to integrate portions of the SDGs into an integrated modelling framework, and each has advantages and disadvantages. The overall ability to incorporate an SDG into a modelling framework will then both depend on the type of model being employed and the specific policy objectives being discussed. Where possible, in our review of the SDGs, we will identify specific model structures that are suited to addressing a given SDG. In many cases we will find that a single modelling paradigm (CGE or optimization) will not be able to address all aspects of a given SDG. In this case, we will discuss what combination might be relevant to addressing the given aspect of that SDG.

The United Nations Sustainable Development Goals (SDGs)

The SDGs (Figure 1) were adopted by the United Nations in 2015 and are aspirational goals that guide nations, UN departments and countries in how to focus their development funding. As noted within the recent modelling advances, there has been some work incorporating land, energy, water and climate impacts into single modelling frameworks, and there has been some work on connecting global whole economy modelling frameworks to optimization frameworks, but there has been no detailed analysis on how to incorporate all 17 goals into systems modelling for sustainable development.

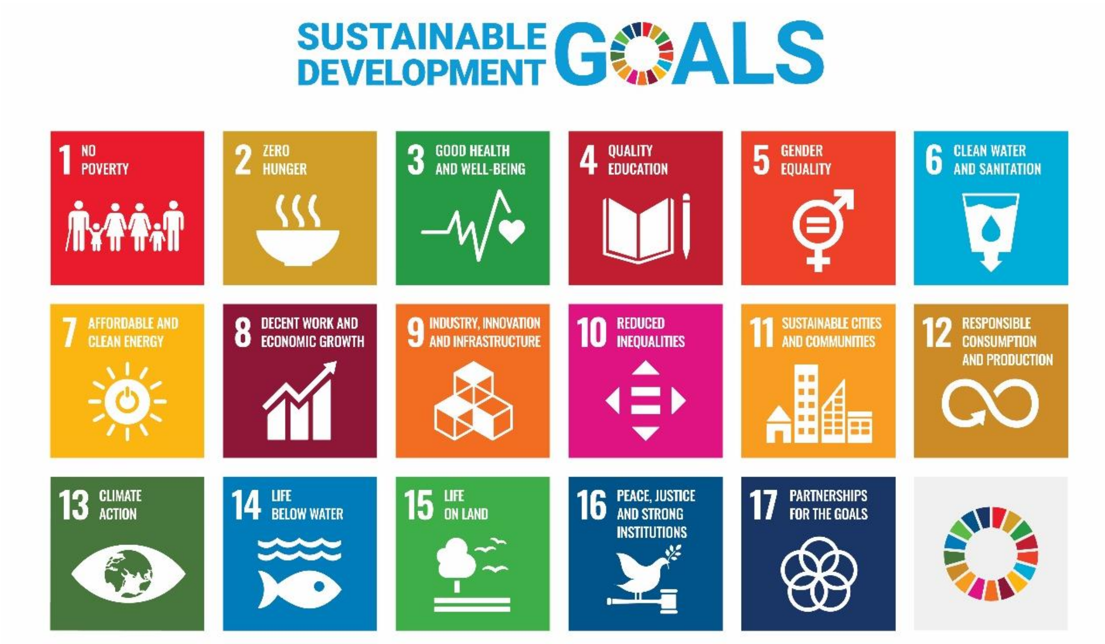


Figure 1: The Sustainable Development Goals

In this section we review each SDG and, from the perspective of systems modelling, consider if any aspects of the goal needs to be incorporated into systems models. For each goal we focus first on the importance of addressing aspects of the given goal in a systems modelling framework and then, where possible, identify how aspects of the given goal can be incorporated into a systems model. In some cases, although it may not be directly possible to incorporate aspects of a goal into a systems model, the goal highlights principles that should be followed in developing models. Following on the work of the International Science Council [17], van Soest et al. [18] and Pradhan et al. [19], we also attempt to identify linkages and feedbacks between the SDGs that may need to be considered when modelling, but we do not repeat this work of identifying linkages between the different goals. Table 2 provides a summary of the ranking for each SDG in each category to summarize the overall discussion.

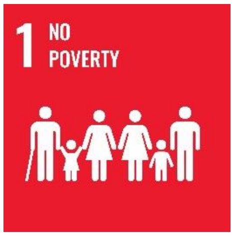
For each SDG, beside the SDG icon, we provide three items: Modelling Required; Ease of Modelling; and Model Structure(s) required. The ranking and icons used are summarized in Table 1. The first, Modelling Required, is an indication of the importance of including this goal in a systems modelling framework, to indicate how important feedbacks and interconnections are to addressing this goal. Modelling required is ranked on a three-point scale, with a white icon indicating this goal does not need to be considered in modelling frameworks or that it is better addressed in other ways; a light blue icon indicating that some modelling may be required, and a dark blue icon indicating that it is not clear how this goal would be addressed without incorporating factors into a modelling framework. For example, goal 7, access to clean and affordable energy is ranked dark blue as it is core to most systems models and, without systems modelling it is not clear how this goal can be addressed. The second item, Ease of Modelling, indicates how easily aspects of this goal can be incorporated into a systems modelling framework. The ease of modelling is ranked on a three-point scale, with a green icon indicating it can easily be modelled, an orange icon indicating some modelling challenges, and a red icon indicating it is not clear how to model this specific goal in any of the above model frameworks. For example, goal 6, clean water and sanitation, is ranked green as it is relatively easy to incorporate into modelling frameworks by tracking both the water needs and the energy and water supplies required to provide this. Finally, we identify which model structures (CGE, optimization) are best suited to addressing this goal. In some cases both are listed as aspects of the goal cross model boundaries. It should be noted that, although we use CGE in the table and discussion below, the whole class of energy-economy models, inclusive of CGE and other energy-economy models such as Input-Output and CIMS are included in this label. And we acknowledge that there are a variety of both linear and non-linear optimization models that include power sector reliability models and capacity expansion models. The labels in the table should thus be taken in a broad rather than a narrow sense.

Table 1: Icons for Ranking SDGs for Modelling

Importance of modelling	Not important
	Some modelling required
	Modelling critical to meeting goal
Ease of modelling	Easily included in systems models
	Some modelling challenges
	Unclear how to include in systems models

Table 2: Summary of the SDGs and the ability to address aspects of this SDG in a modelling framework

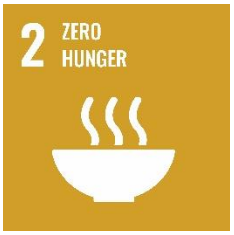
Sustainable Development Goal	Importance of Modelling	Ease of Modelling	Type of Model(s) Required
No Poverty			CGE
Zero Hunger			Optimization
Good Health and Well-being			CGE, Optimization
Quality Education			N/A
Gender Equality			N/A
Clean Water and Sanitation			Optimization
Affordable and Clean Energy			Optimization, CGE
Decent Work and Economic Growth			CGE
Industry, Innovation and Infrastructure			CGE, Optimization
Reduced Inequalities			N/A
Sustainable Cities and Communities			Optimization, CGE
Responsible Consumption and Production			Optimization
Climate Action			Optimization, CGE
Life Below Water			Optimization
Life on Land			Optimization
Peace, Justice and Strong Institutions			Open source models
Partnerships for the Goals			Open source models



Modelling Required: ; Ease of Modelling: ; Model Structure: CGE

The ability to establish a policy that reduces poverty relies on an effective and accurate understanding of the interactions between policy and economic development. In general, from a systems modellers' perspective, this mainly focusses on broader questions such as how to ensure economic development and how to ensure access to affordable services. CGE models, broadly, address the first issue: how to ensure economic development to help lift people out of poverty and are well-established tools for modelling broad economic development. The importance of including poverty reduction policies in economic models to consider the feedbacks between such policies and overall economic health means this SDG is categorized as modelling required in terms of the importance of modelling to address this goal and, in fact, most systems models include some form of economic indicators in their model formulation.

A significant challenge with modelling achievements towards this goal is the unequal distribution of wealth in the economy. General economic growth may not pull the poorest people out of poverty, but most systems modelling structures do not consider the distribution of wealth. As such, we rank this SDG as challenging to include in systems models since there are significant challenges for modelling to address poverty across all levels of society. In addition, access and ability to pay for energy services, food, water and sanitation, a healthy environment, etc. (the focus of other goals) are also precursors to being able to lift people out of poverty, but these are addressed under the relevant goals below. It is also not clear how to incorporate resilience and vulnerability to weather and climate-related events into a systems modelling perspective. These challenges are addressed in a variety of ways in the social sciences literature. See [20]–[22] for examples of how the social sciences approach some of these challenges. The challenge that systems modelling has in addressing the distribution of wealth, as well as the evidence of social sciences approaches to some of these challenges, also needs to be addressed in goal 17: Partnerships towards the goals and will be discussed in more detail there.



Modelling Required: ; Ease of Modelling: ; Model Structure: Optimization

Zero hunger requires both adequate food production, on average, and resilience to weather events that might impact crop yields locally. Adequate food production, including consideration of expected crop yields and consideration of economic ability to purchase and maintain farm equipment such as tractors, irrigation systems and fertilizer are considered in existing optimization modelling frameworks including the CLEWs framework which has been applied in many different contexts and different scales around the globe including cross-boundary jurisdictions such as the Drina river basin [23], [24], for the countries of Mauritius [4] and Burkina Faso [25] as well as for the city of New York [3], [26]. The CLEWs model can consider capital expense for the deployment of, and variable costs for maintenance and operation of farm equipment. Given the existence of models that directly address food availability we rank this goal as definitely required to be considered in modelling structures and easy to incorporate into optimization modelling paradigms.

To further reinforce the fact that this goal needs to be considered in systems modelling it should be noted that this goal is the most inter-connected goal of all 17 as identified by the International Council for Science [17], with strong interconnection to eight other goals. Specifically, there are strong connections between goal 2 and goal 1 (no poverty), goal 3 (good health and well being), goal 5 (gender equality), goal 6 (clean water and sanitation), goal 7 (affordable and clean energy), goal 13 (climate action), goal 14 (life below water) and goal 15 (life on land). Such strong interconnections mean that there are likely many different ways that this goal will be incorporated into systems models and that different model structures will likely highlight different synergies and trade-offs in reaching for this goal.

One piece of the zero-hunger goal that is not well addressed by existing model frameworks is the resilience of agricultural production with extreme weather events and future expected yields under climate uncertainty. There is some work in this area from the Food and Agriculture Organization and IIASA in the Global Agro-Ecological Zones database [27], where global yield predictions for various climate change scenarios are available but, overall, there is still significant uncertainty in this space. Applying uncertainty and scenario analysis within optimization models has been used in the past to address similar uncertainties, but more work is needed. In either case, partnerships (under SDG 17) for the goals to address the resilience of food systems to extreme weather will need to be considered.

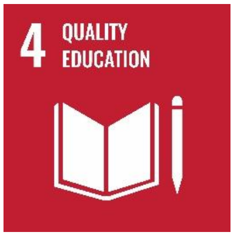
3 GOOD HEALTH AND WELL-BEING

Modelling Required: ; Ease of Modelling: ; Model Structure: CGE, Optimization

The impacts of health on energy services, industrial activity, mobility and goods transport, etc. is extensive, both in terms of negative impacts due to emissions and waste and in terms of positive impacts in terms of enabling access to health services, adequate nutrition, entertainment and leisure activities, etc. There has been significant work in quantifying the health impacts of various industrial activities in the literature, and there are many examples of both negative and positive health impacts of development. The challenge, then, is to adequately quantify the health impacts of different activities and track both the positive and negative health impacts in a model structure and determine how to incorporate these different aspects into systems models. A related challenge is modelling the environmental impacts of health-care related activities such as the impact of waste from health, water and energy use, etc. Hensher [28] provides an overview of the literature on environmental impacts of health care which also needs to be incorporated into modelling structures.

Health impacts can be incorporated into modelling in two different ways. First, CGE models can incorporate the negative economic impacts on overall productivity in a region or country. Second, optimization frameworks can include direct costs of health impacts as well as tracking the impacts of given decisions. For example, in an optimization model, it would be possible to track the health impacts of energy services and then restrict the negative impacts within the optimization structure. This would incur additional costs and a cost-benefit analysis could be undertaken to determine the best policy moving forward.

Although there is significant scope for including health and well-being impacts in systems modelling frameworks, the literature does not have many examples of this type of work. Lott et al. [29] incorporate the impacts of particulate matter (specifically PM2.5 and PM10) into an energy system model and show that ignoring health impacts in the model formulation under-estimates the system costs. Shih and Tseng [30] perform a similar study and find the co-benefits of efficiency measures are more cost-effective when health impacts are taken into consideration. Zvingilaite [31] includes health and other externalities focussing on the localized health impacts to coordinate the siting of energy generation technologies in Denmark. They find that the overall costs can be reduced if health impacts are included in the model formulation. These studies appear to be stand-alone studies and do not provide an overall modelling structure that incorporates health impacts in a systemic and ongoing way, and this is a significant gap in the modelling literature. Gentry et al. [32] discuss the challenge of public health research and notes that the health impacts are often non-linear, and therefore modelling is very challenging. This gap likely leads to sub-optimal outcomes as health impacts and co-benefits are not included in model decision making.



Modelling Required: ; Ease of Modelling: ; Model Structures: -

Although quality education is crucial for meeting many of the other goals, and some aspects of education could potentially be included in model frameworks (such as the availability of labour in CGE frameworks), the overall structure of most models would not easily incorporate quality education into a systems model. As such, the Ease of Modelling for goal 4 is ranked as unclear with the red icon.

That being said, there are links between quality education and the other goals, specifically goal 7 which McCollum et al. [2] notes are critical for schools to have access to lighting, space conditioning as well as many of the modern electronics and tools required for information access and learning technology. These demands should be included in any development path being modelled, and therefore there is some modelling required. Overall this goal is relatively challenging to model, and it is not clear, other than the interaction between available human capital and education and the demands for energy services, how this could be incorporated into any modelling framework.

Modelling Required: ; Ease of Modelling: ; Model Structures: -

Similar to goal 4, goal 5 of gender equality is very challenging to model in any systems modelling framework. And, like goal 4, there are some aspects such as labour availability that would contribute to GDP and therefore be able to be included in certain model structures, but these are not clear and direct links. Therefore, this goal is ranked as unclear how to model with the red icon. However, as modellers build their model structures to consider other goals, it is important that they consider the gender equality implications of the other aspects of their models.

For example, there are many aspects of the gender equality that are reliant on different aspects of systems models, namely access to clean and healthy water and access to energy services. McCollum et al. [2] note that access to energy services such as lighting and clean cooking can greatly enhance gender equity, so as modellers build model structures, the ability to include such aspects into their models is essential. The linkage to zero hunger is also an aspect of gender equality – when there is enough food available and the effort required to gather and prepare food is reduced, there is generally lower gender inequality in societies [17]. Given these interactions, we rank this goal as some modelling required. The model structures best suited to considering these interactions are identified in the other goals, namely goal 7, clean and affordable energy and goal 2 zero hunger.

6 CLEAN WATER AND SANITATION

Modelling Required: ; Ease of Modelling: ; Model Structures: Optimization

Access to clean water and sanitation is both an important goal in and of itself and is identified as linked to goal 2, no poverty, and goal 7, affordable and clean energy by the International Council for Science [17]. This goal requires identifying available water sources in a country, identifying competing demands for said water sources, identifying the energy and other services required to provide clean water, and many other interactions. Since this goal is so critically interconnected with two other goals, and there might be significant trade-offs between different and competing water demands, we rank this goal as critical to be modelled, with a dark blue circle.

Luckily, this goal is also one of the more easily modelled goals and has, in fact, been incorporated into a number of optimization modelling frameworks already, namely the CLEWs[4], [5] and NEST [6], [7] frameworks. Since this goal has already been incorporated into a number of modelling frameworks and synergies and trade-offs between energy, land, and water have already been considered in these frameworks, this goal is ranked as easy to include in systems models.

7 AFFORDABLE AND CLEAN ENERGY

Modelling Required: ; Ease of Modelling: ; Model Structures: Optimization, CGE

Energy models have, for many years, been the core of modelling for sustainable development. Optimization models are used to determine the best and most cost-effective paths for meeting projected energy demands, and CGE models are used to project demand changes based on economic growth, elasticities of substitution and other feedbacks. Within the optimization framework, there is the ability to include impacts of energy services such as climate impacts, land use and water use such as those incorporated into the CLEWs [4], [5] and NEST [6], [7] frameworks. The International Council for Science identifies goal 7 as the second most interconnected goal, with links to goals 1, 2, 3, 6, 8 and 13 [17]. Examples of such interactions include the health impacts (goal 3) of using biomass for cooking as compared to using electricity, or the negative impacts lack of electricity has on industrial development and job creation (goal 8). Given these large number of interactions, goal 7 needs to be incorporated into most model frameworks and, in fact, we see that most model frameworks consider affordable energy as one of the driving factors in the analysis.

8 DECENT WORK AND ECONOMIC GROWTH

Modelling Required: ; Ease of Modelling: ; Model Structures: CGE

There are two inter-related pieces to goal 8. The first, economic growth, is generally modelled with CGE models and is already generally included in many systems modelling frameworks such as GCAM [10] that are based on a CGE structure. This is, however, challenged by the decent work part of the goal. Although the CGE structure can model the overall economic growth, the ability to incorporate aspects of decent work into the goal is more challenging. In addition, incorporating the innovation aspects of the goal may be slightly more challenging as well.

The International Council for Science [17] connects this goal to goal 7, affordable and clean energy, goal 3, good health and well being, and goal 14, life below water. The linkages to affordable energy and good health are clear; this goal might be better addressed by incorporating aspects of those goals into the modelling framework. The link to life below water is likely also best incorporated by considering the emissions and effluent from other systems and methods for mitigating any adverse impacts. Overall, this goal might need some modelling to be considered, and there are some challenges in modelling this goal effectively.

McCollum et al. [2] indicate that strong institutions, especially financial, are necessary for meeting this goal and that energy infrastructure plays a role in creating such institutions to support this goal. This means that the main modelling for this goal is likely to be incorporated by addressing goal 7.

Modelling Required: ; Ease of Modelling: ; Model Structures: CGE, Optimization

The discussion here is almost identical to the discussion for goal 8. Though there might be some aspects of innovation and industry that need to be modelled specifically, in many cases, systems models would not be required to address specific aspects of this goal. McCollum et al. [2] identify that sustainable growth and sustainable industry may need energy infrastructure and this may be something that needs to be considered when modelling. The suitability of existing infrastructure for meeting some of the other goals is also a consideration, but most aspects of this goal can be included by considering goal 7.

One aspect of systems models that may need to be expanded is the focus of optimization models on energy infrastructure. Expanding these models to include consideration of technology and innovation in other industries and sectors would enhance the ability of systems models to guide policy and decisions towards sustainable industrialization. The CLEWs model structure [4], [5], that considers expansion of the farming industry is one example of how other sectors can be included in systems models. A focussed expansion of such models may allow them to provide more context about goal 9.

10 REDUCED INEQUALITIES

Modelling Required: ; Ease of Modelling: ; Model Structures: N/A

Similar to goals 4 (quality education) and 5 (gender equity), goal 10 is very challenging to model, and it is not entirely clear how this could be incorporated into any existing systems modelling frameworks. Nor is it clear what changes to model inputs would occur with increased equity in society.

McCollum et al. [2] identify only weak links to energy in their analysis of the interactions with goal 7 (affordable and clean energy) and note that, in many cases, there are potentially both positive and negative impacts of energy on this goal. For example, if the costs of a transition to lower carbon fuels are born by poorer households, this could increase inequity, but increased access to energy could lift poorer households out of poverty and reduce inequity. Overall, though consideration of equity is needed when discussing policies and their impacts on a system, it is unlikely that there will be any easy ways for this goal to be incorporated in systems models. In addition, it is unlikely that significant impacts on model inputs and outputs would be strongly influenced by this goal.

11 SUSTAINABLE CITIES AND COMMUNITIES

Modelling Required: ; Ease of Modelling: ; Model Structures: Optimization, CGE

Sustainable cities and communities require energy, food, welfare and good health and many aspects of the other goals. For example, McCollum et al. [2] identify that energy is an active driver of ensuring access to basic housing and ensuring that food preparation can be done in sustainable and healthy ways. However, there are some challenges in incorporating city and community-specific aspects of systems into larger systems models. There is opportunity to do so in some cases, and there are examples in the literature of applying systems models to cities and communities (CLEWs in New York [3], A water-energy nexus study of Shanghai [33], A study of the Latrobe Valley near Melbourne, Australia [34] and numerous others).

In many cases, it is not needed to include community-specific features into a broader systems model, and it is often challenging to get data at a disaggregated enough level to be useful for analysing communities and cities in a broad systems context. As such, we rate this goal as some modelling required, but not easy to incorporate into larger systems models.

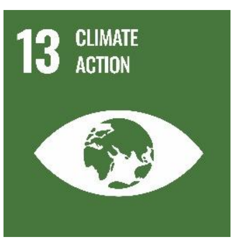
12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Modelling Required: ; Ease of Modelling: ; Model Structures: CGE

Responsible production and consumption are embedded in many of the other sustainable development goals and, in that way, a large portion of this goal is already being modelled. For example, sustainable farming practices are indirectly referenced in goal 13, climate action, goal 3, good health and well being, and goal 7, clean and affordable energy. All these goals consider a few aspects of responsible consumption and production.

However, there are some aspects of this goal that are likely not well considered in most existing modelling frameworks other than by exogenous parameters such as a reduction in demand for plastic bags. Such exogenous methods of incorporating these parameters into a modelling framework may be the only practical way to include this goal in most models since the ability to incorporate such changes in an energy modelling framework is unlikely to provide much benefit.

However, given the importance of consumer decisions in achieving goals such as climate action and good health and well being, it is likely that this goal could use more attention. For example, including the impacts of shifts in consumer behaviour, and the associated shifts in demands for certain products, in a given modelling framework might provide insights as to how to best provision certain energy services in the most responsible and sustainable way. The use of intangible costs in the CIMS model [35]–[37] to determine consumer behaviour is an example of incorporating this goal directly into a modelling framework, but this does not exist broadly in different systems models. This goal has been rated some modelling required to reflect this, and given the challenges of incorporating many different products into most modelling structures, it is also rated as moderately difficult to incorporate.



Modelling Required: ; Ease of Modelling: ; Model Structures: Optimization, CGE

Achieving the climate action goal requires addressing the two different, but equally critical, notions of climate mitigation and adaptation in systems models. Mitigation needs to be considered by incorporating the impacts of the energy and other systems into the modelling framework. This is already done for most systems models, and it is common for model outputs to include costs for reducing carbon dioxide emissions. This gives this goal a rating of modelling required, and also relatively easy to incorporate this into most systems models.

The second aspect of this goal is climate adaptation. This is much harder to model as there is much uncertainty in the impacts of climate change, both on the environment and on society. As an example, there are databases that provide expected attainable crop yields available for various locations such as the global agro-economic zones database [27]. This database has a baseline expected attainable yield and then several different potential yield trajectories. We are not aware of any current work that uses the projected changes in yields to model system dynamics, and there is a significant data management challenge should this be attempted. Other studies have also found that lowered crop yields due to climate change in Africa could reduce GDP growth and cause damage to human health [38]. Parks et al. [39] find that increasing temperatures, and especially anomalous heatwave episodes triggered by climate change, are associated with an increased rate of reported daily injury and deaths. So, although the mitigation aspect of this goal is relatively easy to model, we rank this goal as a moderately challenging to model due to the challenges of incorporating adaptation into systems models.

14 LIFE BELOW WATER

Modelling Required: ; Ease of Modelling: ; Model Structures: Optimization

This goal is relatively situation specific. For example, if building a hydro dam is being considered in the model, then this goal must be modelled in some direct ways. However, a large number of the interactions of the energy system with life below water is driven by either food production from seafood or by the effluent from energy services and generation systems that impact life below water. Although it is important for systems models to be constrained so only sustainable amounts of seafood are available in model outputs, and it is important to track and mitigate emissions and effluent from power systems, overall, this goal does not need a large amount of modelling.

Since some interactions can be cumulative, such that one power plant may not impact the fish stocks in a lake, but multiple plants at the same location could reduce the sustainability of the fish in the lake, there are some challenging threshold effects that may need to be modelled. This makes it somewhat challenging to model this goal in most existing modelling frameworks.

Modelling Required: ; Ease of Modelling: ; Model Structures: Optimization

Goal 15 has some significant similarities to goal 14 in that sustainable land use, in some cases, requires tracking and identification of limitations of the productivity of the land base. However, in contrast to goal 14, humanity has a significant presence on land and has been adapting and changing land use for millennia. From farming to building cities and roads to open-pit mining to flooding large areas of land for irrigation and/or power generation, humanity has an inordinately large impact on land when compared to life below water. This goal interacts with many of the other goals, including goal 2 of no hunger. As such, we rate this goal as definitely requiring modelling as humanity's interactions with land and life on land are so vast.

Luckily, there are modelling structures existing in the literature, such as the CLEWs [4] model that incorporates land use planning in the model formulation. One challenge with the current CLEWs model framework that is not addressed well at this point is a lack of acknowledgement of the life on land, as the current CLEWs methodology focusses mainly on food production and productive use of the land base. Including factors such as the natural capital of forests and grasslands, as well as pastureland, and including consideration of the cumulative impact of land use changes would enhance the ability of the CLEWs framework to address this goal directly. Although there are some challenges with addressing this goal within a modelling framework, we rank this goal as relatively easy to model, given that there are existing frameworks that address most aspects of this goal.

Modelling Required: ; Ease of Modelling: ; Model Structures: Open Source

It is not clear that there is any way to incorporate peace, justice and strong institutions into any existing modelling frameworks in any meaningful way. There is the potential to include higher costs of given policy decisions due to lack of effective institutions in a given jurisdiction and the resulting lower efficacy of the given policy within the society, but this would be challenging, and it is unclear how to justify any given level of reduced efficacy. On the other hand, the existence of peace and justice would contribute to enhanced GDP growth, but again, the link is indirect and not easy to quantify. As such, we rate this goal as very challenging to model in any meaningful way.

Having said that, we also feel that there is little value in attempting to incorporate this goal into a modelling framework. There may be some strengthening of institutions required to meet this goal in given jurisdictions, but this is likely more effectively addressed through foreign aid in building institutions rather than incorporating this into a given model structure.

There is one aspect of this goal that does impact on modeller decision making, however, and that is the ability of institutions in a given jurisdiction to have access to the tools and models for effective decision making. Models which are not accessible, and which cannot be modified and used for policy analysis in various jurisdictions, and/or models which do not provide open data to enable repeatable analysis reduce the ability of governments to have strong and effective policy decision making support. As such, having open models and open data for repeatable and reliable systems analysis is critical to meeting this goal. Luckily there are already a number of models that are available open-source, and there are groups of modellers working together on open-source models [40]–[42].

17 PARTNERSHIPS FOR THE GOALS

Modelling Required: ; Ease of Modelling: ; Model Structures: Open Source

As with goal 16, goal 17 has no specific aspects that are able to be incorporated into modelling structures directly. This means that we rate this a challenge to incorporate any aspects of this goal into a modelling framework. Moreover, as with goal 16, goal 17 has no specific aspects that necessarily need to be incorporated into a modelling framework, and this is therefore rated as no modelling required.

One other aspect of having strong partnerships for the goals is the ability of modellers to use and share their models, and to aid each other in moving modelling forward. This, again, argues for open source models to be utilized for analysis and policy development. There are examples of open-source models being used by partners for sustainable development, such as the capacity development work done by the United Nations Department of Economic and Social Affairs [43]. These initiatives, using open models to ensure low cost and accessibility, and having modellers work together with policymakers and users of the data to enhance policy relevance, allows policymakers to be active participants in modelling and analysis.

Conclusions

The UN Sustainable Development Goals provide a framework to guide countries in building a prosperous and environmentally secure future. Through an in-depth analysis of the 17 SDGs we have shown that there is a need to incorporate many synergies and trade-offs inherent in the goals into systems models. This will help ensure that addressing one goal does not inadvertently impact the ability to achieve others. Though some models are starting to incorporate climate impacts and land and water use in their analysis few models go beyond this scope to address the many different interactions envisioned by the SDGs.

Table 2 summarizes which goals need to be included when expanding the modelling nexus beyond climate, land, energy and water. Specifically, we have rated seven goals as being important to incorporate into modelling frameworks, namely goal 1 (no poverty), goal 2 (zero hunger), goal 3 (good health and well-being), goal 6 (clean water and sanitation), goal 7 (affordable and clean energy), goal 13 (climate action), goal 15 (life on land). As such, a nexus analysis that incorporates climate, land, energy and water, as well as economic well-being, health benefits and impacts and considers land in terms of both food production and in terms of sustaining ecological diversity and natural capital would provide more nuanced systems analysis.

Luckily, most of these goals were also rated either easy or relatively easy to incorporate into modelling frameworks. Addressing poverty requires some additional consideration of equality, both in terms of goal 5 (gender equality), and goal 10 (reduced inequalities) and that poses some challenges for system models. Addressing goal 13 requires some consideration of both sides of the climate change challenge, namely adaptation and mitigation, making it slightly more challenging to incorporate. However, none of the goals rated as critically important to model were rated as impossible or unclear how this could be modelled. Expanding the nexus should, therefore, be feasible and beneficial.

Finally, we note the importance of open-source models and open data for addressing goals 16 and 17. Without open-source models and open data it is unclear how these goals can be met. Having open-source models and open data will allow countries to build their own models and call in the expertise to partner with them rather than being tied to commercial operators whose models are opaque and inaccessible.

Declarations

Ethical Approval and Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors have no competing interests to declare.

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Authors' contributions

All authors discussed the approach and the concept of including the SDGs in energy system modelling. T.N. drafted the manuscript and all authors contributed their expertise, interpretation, and suggestions on the ideas in the manuscript. All authors reviewed and approved the submitted version of the manuscript.

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