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Analysis and control design of sustainable policies for greenhouse gas emissions

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ABSTRACT

Reducing greenhouse gas emissions is now an urgent priority. Systems control theory, and in particular feedback control, can be helpful in designing policies that achieve sustainable levels of emissions of CO_2 (and other greenhouse gases) while minimizing the impact on the economy, and at the same time explicitly addressing the high levels of uncertainty associated with predictions of future emissions. In this paper, we describe preliminary results for an approach where model predictive control (MPC) is applied to a model of the UK economy (UK 4see model) as a test bed to design sustainable policies for greenhouse gas emissions. Using feedback control, the policies are updated on the basis of the actual emissions, rather than on the predicted level of emissions. The basic structure and principle of the UK 4see model is described and its implementation in Simulink is presented. A linearized state space model is obtained and model predictive control is applied to design policies for CO_2 emissions. Simulation results are presented to demonstrate the effectiveness of the proposed method. The preliminary results obtained in this paper illustrate the strength of the proposed design approach and form the basis for future research on using systems control theory to design optimal sustainable policies.

1. Introduction

Global warming is an urgent issue for our planet and finding ways to reduce greenhouse gas (GHG) emissions is now an important research topic. Globally, annual emission now rise to 30.6 gigatonnes of CO_2 per annum, and figures published by the UK Department for Environment, Food and Rural Affairs (DEFRA) show that in 2008, the UK emitted around 533 million tonnes of CO_2 per annum. The draft climate change bill, presented to parliament in 2007, aimed to achieve a 60% cut in emissions by 2050 (compared to 1990 level) as demanded by the Kyoto protocol. This target has been increased to an 80% reduction in emissions by 2050 as set in Climate Change Act 2008 and more recently, an 'interim target' of a 34% cut by 2020 was imposed and made legally binding in the April 2009 Budget. Achieving these GHG emission targets without significantly affecting the UK economy is a major challenge.

A lot of research has been done on the evaluation and design of sustainable policies on climate change and economic growth. For example, in Ref. [1] a roadmap for UK carbon capture and storage (CCS) was developed through a combination of a two-phase process of stakeholder engagement and review of the CCS landscape, Refs. [2,3]. introduced different models to evaluate the economic aspect of the CSS technologies for Europe and China, respectively, Refs. [4,5]. explored the trade-offs between alternative energy system pathways, and the cost, energy supply and emissions implications of these alternative pathways under different scenarios based on the UK MARKAL (MARKet ALocation) dynamic optimisation model and incorporated uncertainties through repeated 'what-if' sensitivity analysis, Refs. [6,7]. introduced the regional integrated model of climate and the economy (RICE model) and used this model to evaluate the effect of carbon price on the climate change and economic growth across different regions. More references can be found in Refs. [8–16].

It is clear that no single factor will generate the required reduction in emissions. Instead, success will require a combination of policies (by policies we mean the detailed strategies and tactics) for deciding the mix of energy generation and reduction in energy usage through the use of incentives, taxes and quotas, and maximising CO_2 absorption, both naturally by preserving forests and via technical developments, such as carbon capture and storage. It is also clear that implementing these policies will have an impact on economic growth and, as the Stern report emphasises [17], acceptance of these policies will only be achieved if the impact on economic growth is minimized. In addition, it is noted that there are uncertainties/disturbances associated with the effect of the policies on the CO_2 emission rate and economic growth. Therefore, any policy design must take modelling

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uncertainties into account and the policies should be updated based on the current situation (i.e. using a feedback mechanism to update the policies according to actual emissions rather than predicted values) to compensate for the effect of unexpected disturbances.

The design objective can be stated as designing a sustainable policy that achieves sustainable levels of emissions of CO_2 (and other greenhouse gases) while minimizing the impact on the economy. The aim of the designed policy is to adjust factors such as the mix of energy generation methods and policies for reducing emissions from housing, industry and transport based on current situation, in order to achieve a rate of emissions that will allow UK to achieve its emissions targets while maximising economic growth. This can be considered as an optimal control problem and therefore concepts from modern systems control theory (and in particular, feedback) can be used to develop design algorithms. The feedback mechanism updates policies on the basis of the actual rather than predicted emissions, and hence provides a degree of robustness against noise/disturbances. The high levels of uncertainty associated with predictions of future emissions can also be addressed systematically using systems control tools.

The above approach is currently being implemented on the UK 4see model, which describes the dynamic evolution of the UK economy and CO_2 emissions based on the ECCO (Evolution of Capital Creation Options) modelling methodology [18–22]. Compared to other energy economic models (e.g. computable general equilibrium model GEM-E3 [23], or the optimization based MARKAL model [4,5]), the 4see model is a system dynamics model based on general systems theory and thus, is more suitable as an initial test bed for verifying our proposed systems control theory-based design methods. In the future, the tools for control design will be applied to other existing models.

As a preliminary result of this approach, in this paper, Model Predictive Control (MPC) is applied to the UK 4see model to design sustainable policies to demonstrate the potential power of using systems control theory to control greenhouse gas emissions. The paper is organised as follows. In Section 2, the basic structure and principle of the UK 4see model is explained. An initial version of the model in VenSim (a system dynamics modelling simulation software) was converted into Simulink to allow more flexibility in control system analysis and design. The resulting UK 4see model is highly nonlinear and to facilitate the design process, a linearized model is obtained and analysed in Section 3. In Section 4, model predictive control is applied to the linearized model to design sustainable policies and simulation results are presented. Finally, conclusions and future research directions are given in Section 5.

2. UK 4see model and Simulink implementation

2.1. ECCO modelling methodology

The UK 4see model is a dynamic model of the UK national economy based on the ECCO (Evolution of Capital Creation Options) modelling methodology [18–22,24]. It was firstly developed in the Dynamo simulation language by a research group from University of Edinburgh in 1992 and recently, an improved version, on which this paper is based, was developed in VenSim environment by the Innovation & Foresight unit at Ove Arup (where the model was renamed as 4see instead of ECCO [25,26]). ECCO uses a macroeconomic holistic modelling approach for determining the system-wide, long term effect of implementing policy options at the national/regional level. It does this by determining the growth potential of the economy in the context of the existing economic structure and user-defined policies, technology options and environmental objectives. Changes in growth potential in turn alter a wide range of demand and supply terms, and so reflect many other aspects of the evolving economy [24]. The ECCO model emphasises the feedbacks between sectors and the impacts of the policy upon the endogenously determined rate of physical growth. It was originally intended to be used in assessing the compatibility of multiple goals prior to their adoption by policy-makers and mainly addresses the question [18,27], ‘What would happen if a set of policies are to be set?’ However, in this research the model is used as the basis of an optimal control design.

To develop an ECCO model, the main economic sectors are identified, which include both human-made capital sectors (e.g. industry and agriculture) and natural capital stocks (i.e. energy and material resources). As the states within the system evolve with time, the size of each sector will change and the changes in one sector will affect the growth of other sectors through cross sector interactions. The internal dynamics and interactions between different sectors are characterised through the physical principles of mass and energy balances as measured by embodied energy [24]. The exact parameters of these dynamics are determined either empirically or by validating against historical statistical data for a specific period as obtained from government sources of statistics (e.g. DUKES DUK [28], Blue Book BLU [29] and Pink Book PIN [30]).

2.2. UK 4see model

The UK 4see model consists of thirteen sectors of the UK economy, namely: industry and growth, balance of payments, services, dwellings, standard of living, employment, resource and mining, electricity generation, transport, agriculture, water, global and sectoral coefficients, and carbon dioxide. The model was implemented in VenSim environment into 13 views (subsystems) and each view corresponds to one sector. More details about the model can be found in the Appendix and [24–26] and here, we take the carbon dioxide sector shown in Fig. 1 as an example to illustrate the basic idea and structure of the model.

In Fig. 1, each name in the diagram is a variable, e.g. CO_2 *released by oil* (unit: tonnes/year), *oil demand* (unit: VPJ/year, i.e. virtual petajoules calculated using embodied energy [24]) and CO_2 *generated index* (unit: tonnes/year). The value of a variable is either determined by external input data (e.g. energy policies) or by the variables connected to it. The connections between variables represent mathematical operations, which are governed by mass or energy balance. The pipeline connections represent integral operations; for example in this figure according to mass balance the value of CO_2 *generated index* is determined by

$$\frac{\mathrm{d}(CO_2\ \textit{generated index})}{\mathrm{d}t} = RF\ CO_2 - old\ CO_2 \tag{1}$$

where $RF\ CO_2$ is the rate of CO_2 formulation (unit: tonnes/year) and *old* CO_2 is the previous CO_2 production rate. In the *electricity generation* sector the electrical energy generated by thermal power plant measured by gigawatt (GW) is determined by

$$\frac{\mathrm{d}(\textit{Thermal generating capacity})}{\mathrm{d}t} = \textit{rate of building Thermal} - \textit{rate of depreciation Thermal} - \textit{rate of decommissioning of Thermal}. \tag{2}$$