Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model

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Abstract In this study, we develop a new integrated assessment model called the BET model
(Basic Energy systems, Economy, Environment, and End-use Technology Model). It is a multi-
regional, global model based on Ramsey's optimal growth theory and includes not only traditional
end-use technologies but also advanced end-use technologies such as heat-pump water heaters
and electric vehicles. Using the BET model, we conduct simulations and obtain the following
results. (1) Advanced end-use technologies have an important role in containing carbon prices as
well as GDP losses when GHG (greenhouse gas) constraints are stringent. (2) Electrification
based on energy services progresses rapidly in scenarios with stringent GHG constraints. This is
because electricity can be supplied by various methods of non-fossil power generation, and
advanced end-use technologies can drastically improve energy-to-service efficiencies. The
BET's results indicate the importance of analyses that systematically combine environmental
constraints, end-use technologies, supply energy technologies, and economic development.

1 Introduction

To guide policy discussions for long-term, global sustainable development, it is necessary to
evaluate interactions between energy, the economy, and the environment. Analysts have utilized

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IAMs (integrated assessment models) to evaluate such interactions. To date, a number of analyses have been conducted to assess climate policy (Weyant 1999, 2004; Weyant et al. 2006).

Recently, advanced end-use technologies have received increasing attention as a key component of options for climate change mitigation (Kyle et al. 2011). In particular, advanced electric technologies are found to play an important role. Electric end-use technologies are promising since they are increasingly affordable and present high end-use efficiencies. Combined with various types of non-fossil power generation technologies, they lead to an increased share of electricity in the final energy consumption (Manne and Richels 1992; Edmonds et al. 2006; Sugiyama 2012 and references therein). To realistically assess the potential of end-use efficiency and electrification, IAMs need to realistically represent supply and end-use technologies as well as macroeconomic effects such as substitution between energy and capital/labor.

Many of the contemporary IAMs are increasingly capable of representing technological detail and economic interactions because of continuing trend of hybridization (Sugiyama et al. 2013). Partial equilibrium models such as TIAM (Loulou and Labriet 2008), POLES (Criqui et al. 1999), AIM/Enduse (Kainuma et al. 2000), and DNE21+ (Akimoto et al. 2008), incorporate some degree of economic effects. On the other hand, general equilibrium models such as MERGE (Richels and Blanford 2008) and ReMIND (Leimbach et al. 2010) nowadays explicitly incorporate end-use technologies within a macroeconomic framework in a global IAM based on Ramsey's optimal growth theory, extending classical IAMs (Nordhaus 1994; Manne et al. 1995). WITCH (Bosetti et al. 2006) is a top-down neoclassical optimal growth model with a specification of energy services. MESSAGE-MACRO (Messner and Schrattenholzer 2000) links an energy supply model (Schrattenholzer 1981) with a macroeconomic module and solves it iteratively.

Nevertheless, more progress is needed to systematically understand the role of end-use energy efficiency. This is because, although energy efficiency is a very old topic, the economy-wide effect of advanced end-use technologies is a relatively new one (Kyle et al. 2011). In fact, many of the IAMs of the top-down origin have explicit representation of the transport sector, but not of industry and buildings sectors (Sugiyama et al. 2013).

Herein, we present a new model called the BET (Basic Energy systems, Economy, Environment, and End-use Technology) model that also includes explicit end-use representation in a global IAM based on Ramsey's optimal growth theory. It is strongly influenced by MERGE (Manne et al. 1995; Richels and Blanford 2008) and MARKAL-MACRO (Loulou et al. 2004), which is closely related with TIAM.

The feature of the BET model is to include several advanced end-use technologies using electricity such as heat pump water heaters for industry, commercial, and household. Although qualitatively speaking, most of our results here are reconfirmation of previous studies, the BET model enables us to examine the role played by electrification and advanced end-use technologies to achieve a certain climate target more systematically, ranging from changes in usage of end-use technologies to power generation mix.

2 The BET model

This section describes the BET model's structure (Fig. 1), modules, and parameters. The details of the model structure and parameters are described in the Electronic Supplementary Material (ESM).

The BET model is a neoclassical optimal growth model hard-linked with an energy systems module, which includes both energy supply technologies and end-use technologies,
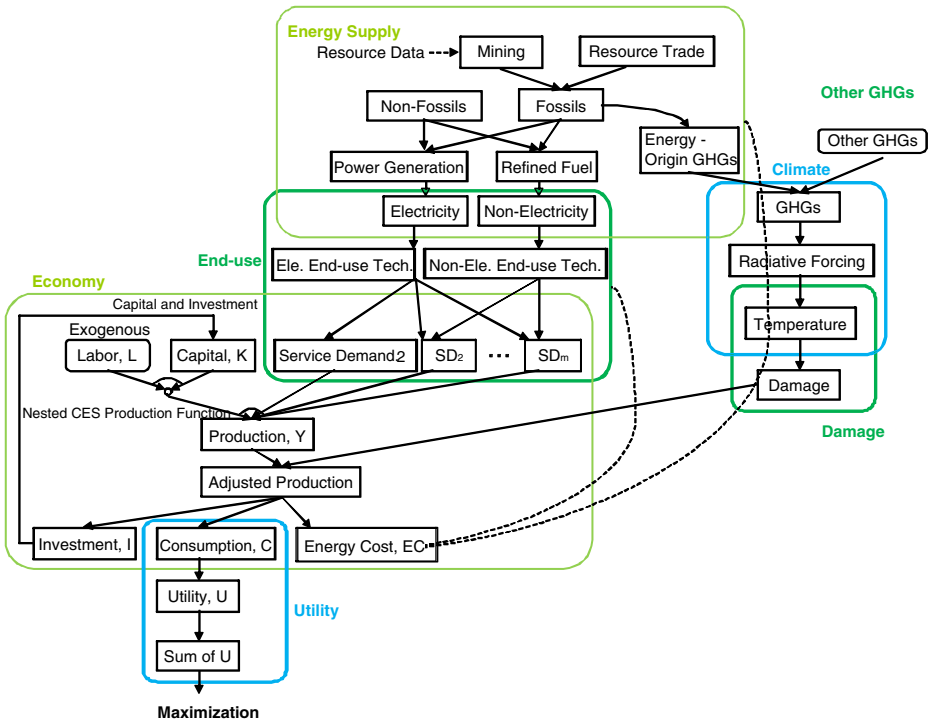
Fig. 1 Schematic of the structure of the BET model. The BET model consists of economic module, energy module including end-use module, and climate module

and a climate module (not used in this study). Roughly speaking, the BET model can be summed up as "a MERGE with advanced, electric end-use technologies" or "a global MARKAL-MACRO with limited technologies".

The macroeconomic production function is identical to that of MARKAL-MACRO (Loulou et al. 2004), the inputs of which are not final energy amounts but energy services. Since MARKAL-MACRO is a regional model but the BET model is a global model, the latter solves a market equilibrium as a social planner's problem using Negishi weights (Negishi 1960).

The energy systems module, the structure of which is similar to that of MARKAL-MACRO (Loulou et al. 2004), describes not only energy supply systems such as mining, fuel conversions, and power generation, but also end-use systems such as end-use technologies that convert final energy to energy services. The end-use technologies in the BET model, which are simplified compared with those in MARCAL-MACRO of the regional model with detailed end-use technologies, include advanced technologies such as heat-pump water heaters for industry, commercial and residential, and electric vehicles for road passenger services in order to evaluate the mitigation effects of advanced electrification technologies.

The BET model includes a simple carbon-climate module called SEEPLUS, the carbon cycle of which simulates nonlinear processes of natural CO_2 absorption using climate impulse functions (Tsutsui 2011). The simple carbon-climate module is not active in this study, since the climate targets of the BET model are not CO_2 concentrations but rather CO_2 emission budgets in the EMF27 protocol (Kriegler et al. 2013).

The world is divided into 13 regions: the USA (United States of America), EU27 + 3 (European Union 27 plus Iceland, Switzerland, and Norway), CANZ (Canada, Australia,

and New Zealand), Japan, Russia, China, India, Other Asia, Other Europe (including countries in the Former Soviet Union except Russia), MENA (Middle East and North Africa), Sub-Sahara Africa (including South Africa), Brazil, and Other Latin America. The calculation period is 2000 to 2230 with a 10-year time step, although the reporting period is until 2100 in EMF27. The calculation period is extended beyond 2100 to avoid terminal effects.

The BET model is written in the GAMS (Brooke et al. 1992) language, with all modules packaged into one.

2.1 Model structure

2.1.1 Economic module

The production function in the BET model is a one-sector, nested CES (constant elasticity of substitution) function, the format of which is the same as the MARKAL-MACRO (Loulou et al. 2004). The function is a putty-clay function that considers the vintage of capital:

$$YN_{t,r} = \left\{ a_{t,r} \left(KN_{t,r} \right)^{\rho\kappa} \left(LN_{t,r} \right)^{\rho(1-\kappa)} + \sum_i b_{i,t,r} \left(DN_{i,t,r} \right)^{\rho} \right\}^{\frac{1}{\rho}},$$

where YN is an incremental change in output, KN is an incremental change in capital, LN represents an increment in labor, and DN is an incremental change in energy service. a and b represent the coefficients for value added and energy services, respectively. The parameter ρ is defined as $\rho = (esub\text{-}1)/esub$, where $esub$ is the elasticity of substitution between the capital/labor aggregate and the aggregate of energy services. The parameter κ is the capital distribution factor. The subscripts t,r and i indicate time, regions, and types of energy services, respectively. We express economic variables in market exchange rates.

Note that the present formulation of production function prohibits trade-off of labor assignment between energy and non-energy sectors of the economy; labor does not enter the nest of energy. Also, the single-nest structure allows only for a single value of elasticity of substitution, $esub$, although. In reality, some energy services have a high elasticity while others low.

The economic output in each year, $Y_{t,r}$ is calculated as

$$YN_{t,r} = Y_{t,r} - speed_t Y_{t-1,r},$$

where $speed_t = (1\text{-}depr)^{nyper_t}$. Here, $depr$ is the depreciation rate and $nyper_t$ is the number of years in each period, which is 10. Capital, $K_{t,r}$, Labor, $L_{t,r}$ and energy services, $D_{i,t,r}$ can be similarly defined. Since investment is measured as annual flow, capital $K_{t,r}$ is depreciated as follows.

$$KN_{t,r} = \left(I_{t,r} + speed \cdot I_{t-1,r} \right) \cdot nyper_t / 2 ,$$

where I is investment.

The production Y, is equal to the sum of consumption C, investment I net export (NTX) of composite consumer goods(nmr), and energy systems cost EC:

$$Y_{t,r} = C_{t,r} + I_{t,r} + EC_{t,r} + NTX_{nmr,t,r}$$

The net export of composite consumer goods as well as the other tradable goods must add up to zero over the globe:

$$\sum_r NTX_{trd,t,r} = 0,$$

where trd consists of nmr, crt (carbon credit), and $fuel$ (coal, oil, and gas).

To solve for a market equilibrium, we pose a social planner's maximization problem using a Negishi weight method (Negishi 1960). For each region, the utility function of the model is the logarithm of the consumption, $C_{t,r}$. The model maximizes the sum of regional discounted utilities:

$$U = \sum_{t,r} \theta_r \, df_{t,r} \log C_{t,r},$$

where θ_r is the iteratively determined Negishi weight (Negishi 1960; Leimbach and Toth 2003) and $df_{t,r}$ is the discount factor. The discount factor is determined by the pure rate of time preference, $udr_{t,r}$:

$$df_{t,r} = \Pi_{t' < t} \left(1 - udr_{t',r} \right)^{nyper_{t'}}$$

The major parameters of economic module are explained in the ESM.

2.1.2 Energy module

The energy module in the BET model calculates the energy system cost (*EC* in the previous section) corresponding to the supply of energy services (*DN* and *D* in the previous section). The energy module is formulated with linear functions and constraints. The primary energy in the BET model consists of coal, oil, natural gas, biomass, nuclear, hydro, wind, photovoltaic, geothermal, electric-backstop, and gaseous-backstop.

The final energy consists of solid, liquid, gaseous, and electricity. Coal can be converted to synthetic oil. Biomass can be converted to solid, liquid, and gaseous fuels.

The power generation sub-module in BET takes into account capacity constraints and the lifetime of each generation plant. In addition, it considers the load duration curve, discretized into four sections, ranging from year maximum hours, peak hours, shoulder hours, to bottom hours. Though crudely, this captures some aspects of economic dispatch control of the power systems. Since it does not incorporate adjustments for fluctuations on shorter timescales (e.g., via load frequency control), BET has a generation constraint on solar and wind, which are intermittent renewables (see the ESM). Each generation technology has its own characteristics so that the model endogenously solves for the capacity and power mix.

In the BET model, there are 20 kinds of energy services (Table 1). Out of the 20, eight services have competing technologies. There are 31 competing technologies in total, including heat pump water heaters and traditional fossil boilers (see the ESM). For the remaining 12 services, the amounts of energy services are essentially equivalent to final energy demands (aside from some coefficients to adjust for efficiencies).

In modeling energy services, we followed and simplified the approach used by the UK MARKAL (UK Energy Research Centre 2010), as the BET model is a long-term, global model, in contrast with the UK MARKAL, which focuses on domestic analyses. Since the BET model enables us to examine the role played by electrification and advanced end-use technologies, it includes 11 kinds of electric end-use technologies such as heat pump water heaters and electric passenger vehicles of 31 kinds of all end-use technologies. However, the model does not include non-electric end-use technologies such as hybrid passenger vehicles and fuel cell vehicles in the transportation sector. These technologies will be included in the future study.

The list of end-use technologies is short, and will be expanded in the future. Because of lack of many end-use technologies, aggregate energy demands are created (see the entries of "other" in Table 1). This ensures that the energy consumption in BET matches the observed value in the calibration year.

Table 1 Relation between final energy demands and energy services. In the BET model, there are 20 kinds of energy services. Out of the 20, eight services (shown in italic) have competing technologies. There are 31 competing technologies (shown in italic) in total, including heat pump water heaters and traditional fossil boilers (see the ESM). For the remaining 12 services, the amounts of energy services are essentially equivalent to final energy demands (aside from some coefficients to adjust for efficiencies). For space heating in the commercial sector and the residential sector, no new stove with solid fuels is assumed to be allowed. Liquid for other services in the commercial sector and household sector is introduced to reflect the energy usage in the base year. The technology shares for cooking services do not change in the future. The railroad's shares do not change with time either. Road passenger includes two and three wheel vehicles

Sector	Sub-sector	Electricity	Solid fuel	Liquid fuel	Gaseous fuel
Industry	*High-temp. heating*	*Electric heating/ Inductive heating*	*Solid boiler*	*Liquid boiler*	*Gas boiler*
	Low-temp. heating	*Electric heating/ Heat pump*	*Solid boiler*	*Liquid boiler*	*Gas boiler*
	Other electricity	Electricity	N/A	N/A	N/A
	Other solid fuel	N/A	Solid fuel	N/A	N/A
	Other liquid fuel	N/A	N/A	Liquid fuel	N/A
	Other gaseous fuel	N/A	N/A	N/A	Gaseous fuel
Commercial	Lighting	Electricity	N/A	Oil lamp	N/A
	Space cooling	Ele. air con.	N/A	N/A	N/A
	Cooking	Ele. cooker	Solid cooker	Liquid cooker	Gas cooker
	Hot water	*Electric heating/ Heat pump*	N/A	*Liquid*	*Gas*
	Space heating	*Ele. Heat pump*	*Solid stove*	*Liquid stove*	*Gas stove*
	Other	Electricity	N/A	N/A	N/A
Household	Lighting	Electricity	N/A	Oil lamp	N/A
	Space cooling	Ele. air con.	N/A	N/A	N/A
	Hot water	*Electric heating/ Heat pump*	*Solid*	*Liquid*	*Gas*
	Cooking	Ele. cooker	Solid cooker	Liquid cooker	Gas cooker
	Space heating	*Ele. Heat pump*	*Solid stove*	*Liquid stove*	*Gas stove*
	Other	Electricity	N/A	N/A	N/A
Transportation	*Road freight*	N/A	N/A	*Conv. vehicle/ Hybrid vehicle*	N/A
	Road passenger	*Electric vehicle*	N/A	*Conv. vehicle*	N/A
	Railroad	Electricity	N/A	Liquid	N/A
	Aviation and shipping	N/A	N/A	Liquid	N/A

3 Results

This section presents the results of the BET runs, with a particular focus on the role of advanced end-use technologies such as heat pumps.

3.1 Scenarios

Our focus is on Base FullTech, 550 FullTech, 450 FullTech (Kriegler et al. 2013) and 650 FullTech. The target numbers such as 450, 550, and 650 indicate greenhouse gas stabilization concentrations in units of parts per million in CO_2 equivalent (ppm-eq). The 650 FullTech is not included in the

standard scenarios of the EMF27, but we have added this scenario to explore emissions constraints more thoroughly. CO_2 emissions from industrial processes are exogenously given and are common across scenarios, except for the 450 FullTech scenario, for which they are set at one-third the standard values. Since we do not discuss the scenarios with limited technological options such as nuclear-off and CCS-off determined in EMF27, we hereafter drop "FullTech" from the scenario names.

We also ran the scenarios with advanced end-use technologies turned off in order to explore their role. In particular, the following technologies are excluded: industrial induction heaters and industrial heat-pump heaters, heat-pump water heaters in commercial and residential sectors, freight hybrid trucks, and passenger electric vehicles. We call these runs Base-off, 650-off, 550-off, and 450-off scenarios, each corresponding to the Base, 650, 550, and 450 scenarios.

3.2 GDP losses

Figure 2 shows the percentage changes in GDP of each scenario relative to the Base scenario (See the ESM for GDP in the Base scenario.) Turning off advanced end-use technologies results in GDP losses, even in the baseline (Base-off). Such losses become larger with a more stringent climate policy. The differences in GDP loss caused by the on-off state of the advanced end-use technologies are 0.4 % between the Base and the Base-off, 1.0 % between the 650 and the 650-off, 2.1 % between the 550 and the 550-off, and 3.1 % between the 450 and the 450-off. These results suggest that advanced end-use technologies are a promising option to contain GDP loss when the climate target is stringent.

3.3 Total primary energy supply and power generation mix

The total primary energy supply (TPES) in the Base scenario increases to 977EJ in 2050 and 1,446EJ in 2100, which is about 10 % larger than that in SRES B2. CO_2 constraints decrease TPES. TPES in 2100 stands at 882EJ, 789EJ, and 725EJ in the 650, 550, 450 scenarios, respectively (see Fig. 3 in the ESM).

The fossil fuel consumption is affected by climate policy. In 2100, the fossil fuel consumption is 1,139EJ in the Base scenario, which decreases to 429EJ, 341EJ, 281EJ in the 650, 550, and 450 scenarios, respectively. The coal consumption in 2100 similarly drops substantially, from 784EJ in the Base scenario to 17EJ in the 650 scenario, 5EJ in the 550 scenario, and 2EJ in the 450 scenario.

Fig. 2 GDP index. The GDP in Base scenario is 100. The difference of GDP index caused by the availability of advanced technologies is large when the GHG constraint is strict
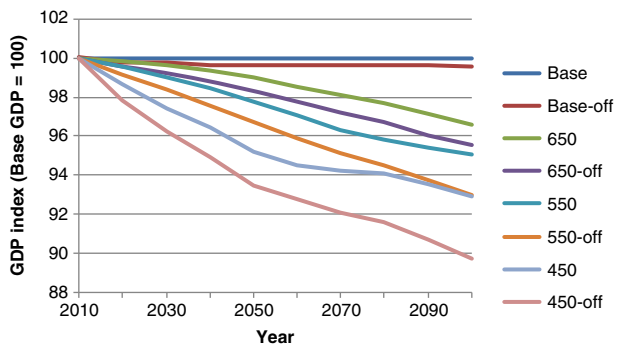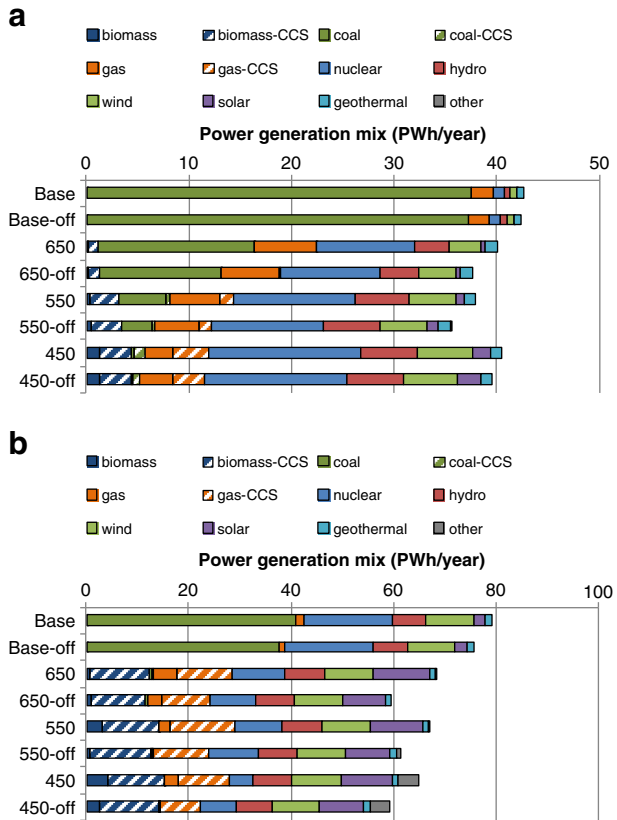
Fig. 3 Power generation mix in the world. **a**: 2050 and **b**: 2100

Global electricity generation increases from 16 PWh in 2010 (BET's result, not from energy statistics) to 43PWh in 2050 and 79PWh in 2100 in the Base scenario. Electricity generation is not sensitive to climate policy. There are various low-carbon electricity supply technologies such as non-fossil-fuel technologies and carbon capture and storage (CCS). These ensure that the demand for electricity remains relatively unaffected by GHG constraints.

The composition of electricity generation, however, differs markedly across scenarios (Fig. 3). In the Base scenario without carbon constraints, coal (without CCS) dominates electricity generation, providing over 80 % of the total in 2050 and approximately 50 % in 2100. In 2100, other technologies make penetration as well, with nuclear energy providing about 22 %, hydropower 8 %, and wind energy 12 %. By imposing a climate policy, power generation using coal without CCS is cut down. In 2050, its share reduces to 38 %, 12 %, and 1 % in the 650, 550, and 450 scenarios, respectively. Coal's role diminishes further in 2100, with its share dropping to a mere 1 % even in the 650 scenario. The preferred generation technologies under climate policy are biomass and gas, both with CCS. Biomass with CCS contributes 17–19 % and gas with CCS 16–19 % to power generation in 2100. As climate policy becomes more stringent, more solar and wind is introduced. In the 450 scenario, the shares of solar and wind in 2100 are 14 % and

15 %, respectively. Note that it is assumed the ceiling of solar and wind penetration at 30 % (see the ESM).

A comparison of the 650, 550, and 450 scenarios with the 650-off, 550-off, and 450-off scenarios reveals that advanced end-use technologies allow for an increase in electricity generation. In 2050, electricity generation in the scenarios with GHG constraints is larger by about 2–6 % than that without advanced end-use technologies, and in 2100, by about 5–14 %.

3.4 CO_2 emissions and carbon prices

The primary energy supply in the Base scenario without GHG constraints increases monotonically, and coal occupies the largest share in primary energy supply. Thus, global CO_2 emissions continue to increase. The global CO_2 emissions, which are the sum of emissions from fossil fuel, industrial processes, and land-use changes, increase from 31 Gt-CO_2 in 2010 (model value, not observation) to 71 Gt-CO_2 in 2050 and 93 Gt-CO_2 in 2100 (see Fig. 4 in the ESM).

The CO_2 emissions are reduced in the scenarios with GHG constraints. The CO_2 emission in 2100 is reduced to 10 Gt-CO_2 in the 650 scenario, 4.7 Gt-CO_2 in the 550 scenario, and 1.1 Gt-CO2 in the 450 scenario. The availability of the advanced end-use technologies does not affect the CO_2 emission paths clearly, since the CO_2 budget constraints virtually prescribe the shapes of the emission paths.

CCS technologies are introduced on a large scale in the scenarios with GHG constraints. The amounts of CCS in 2050 are 1 Gt-CO_2 in the 650 scenario, 4 Gt-CO_2 in the 550 scenario, and 6 Gt-CO_2 in the 450 scenario. The amounts of CCS in 2100 are 17 Gt-CO_2 in the 650 scenario, 17 Gt-CO_2 in the 550 scenario, and 16 Gt-CO_2 in the 450 scenario. The amounts of CCS in the scenarios with GHG constraints are close in 2100. This is because the cumulative amounts of CCS in the scenarios with GHG constraints are close to the limit of the carbon storage capacity.

The large portion of the introduced CCS is occupied by BECCS (Bio-Electricity with Carbon Capture and Storage). For example, the ratio of BECCS to the total CCS in 2100 is 78 % in the 650 scenario, 76 % in the 550 scenario, and 79 % in the 450 scenario. BECCS is a key technology to reduce CO_2 emissions on a large scale.

As GHG constraints become stricter, the carbon prices increase. The carbon prices in 2050 are \$52/t-CO_2 in the 650 scenario, \$128/t-CO_2 in the 550 scenario, and \$365/t-CO_2 in the 450 scenario (Fig. 4). The carbon prices in 2100 are much more higher than those in 2050. The carbon prices in 2100 rise to \$405/t-CO_2 in the 650 scenario, \$995/t-CO_2 in the 550 scenario, and \$ 2,842/t-CO_2 in the 450 scenario.

Fig. 4 Carbon prices. The difference of carbon prices caused by the availability of advanced technologies is large when the GHG constraint is strict
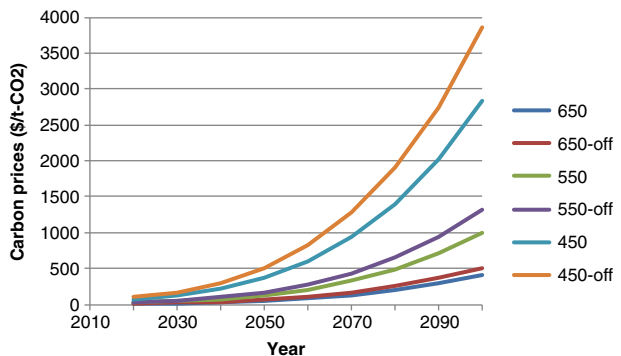
The advanced end-use technologies can affect the carbon prices. The carbon prices in 2050 are \$65/t-CO_2,\$170/t-CO_2,\$502/t-CO_2 in the 650-off, 550-off, and the 450-off scenarios, respectively. Each price is higher than in the equivalent scenario with the advanced end-use technologies. The carbon prices in 2100 are \$511/t-CO_2, \$1,314/t-CO_2, \$3,856/t-CO_2,the 650-off, 550-off, and 450-off scenarios. These carbon prices are larger by \$106/t-CO_2, \$319/t-CO_2, \$1014/t-CO_2 than those in the corresponding scenarios with the advanced end-use technologies. Hence, the advanced end-use technologies are important in order to reduce the carbon prices, especially in the scenarios with stringent GHG constraints.

3.5 Final energy, energy services, and electrification rate

The final energy demand stands at 347 EJ in 2010, which is calculated by the BET model and does not accurately conform to the IEA statistics (IEA 2010). It increases substantially with time, roughly doubling in 2050, and tripling in 2100 (Fig. 5). Energy services generally take various units (vehicle-km-traveled for passenger transportation and GJ for heating, for instance), and are not amenable to comparison across sectors. Here, we choose to represent energy services in energy units, using the efficiencies listed in Table 2 of the ESM.

When the GHG constraints are strict, the final energy demands decrease on a large scale. The final energy demands in the 650, 550, and 450 scenarios in 2050 are lower by 18 %, 29 %, and 45 %, respectively, as compared to those in the Base scenario. The CO_2 emissions in the 650, 550, 450 scenarios in 2100 are lower by 40 %, 49 %, 55 %, respectively, as compared to those in the Base scenario (Fig. 5).

The simulation results show that the electricity demand is relatively stable (see 3.3), but the non-electricity demand decreases as the GHG constraints become more stringent (Fig. 5). This is because electricity can be supplied by various low-carbon options such as renewables, nuclear, and fossils with CCS, but non-electricity supply is limited to a few low-carbon options such as biomass. Hence, the electrification rates based on the total final energy supply increase, when the GHG constraints are stringent. The electrification rates on the total final energy supply in the Base scenario without GHG constraints increase from 15 % in 2010 to 19 % in 2050 and 24 % in 2100. Furthermore, the electrification rates in the scenarios with GHG constraints increase rapidly. The electrification rates with GHG constraints in 2050 increase to 22 % in the 650 scenario, 24 % in the 550 scenario, and 33 % in the 450 scenario. The electrification rates in 2100 reach 35 % in the 650 scenario, 41 % in the 550 scenario, and 44 % in the 450 scenario.

Since the BET model includes end-use technologies, it can calculate energy services. The simulation results show that the advanced end-use technology of hybrid trucks supplies road freight services but the advanced electric end-use technologies do not supply any services in 2050 in the Base scenario. As the GHG constraints become stricter, the advanced electric end-use technologies such as heat-pump water heaters supply more energy services.

The amount of the energy services using electricity is more stable than that of the other energy services under stringent GHG constraints (Fig. 5). This is because the advanced electric end-use technologies with high energy efficiency can supply a large amount of energy services for a small amount of electricity. The non-electric energy services decrease under stringent GHG constraints, since only an advanced non-electric end-use technology, i.e., hybrid truck technology in the road freight sector, is available in the BET model.

Hence, the electrification rates based on energy services are high under stringent GHG constraints. The electrification rate in the Base scenario without GHG constraints increases moderately from 25 % in 2010 to 41 % in 2100. The electrification rates in the scenarios

Fig. 5 Supply of final energy and energy service. **a**: Final energy supply in 2050, **b**: energy service supply in 2050, **c**: final energy supply in 2100, and **d**: energy service supply in 2100. Energy services are shown in the energy unit and the conversion efficiencies from final energy to energy services are shown in Table 2 in the ESM
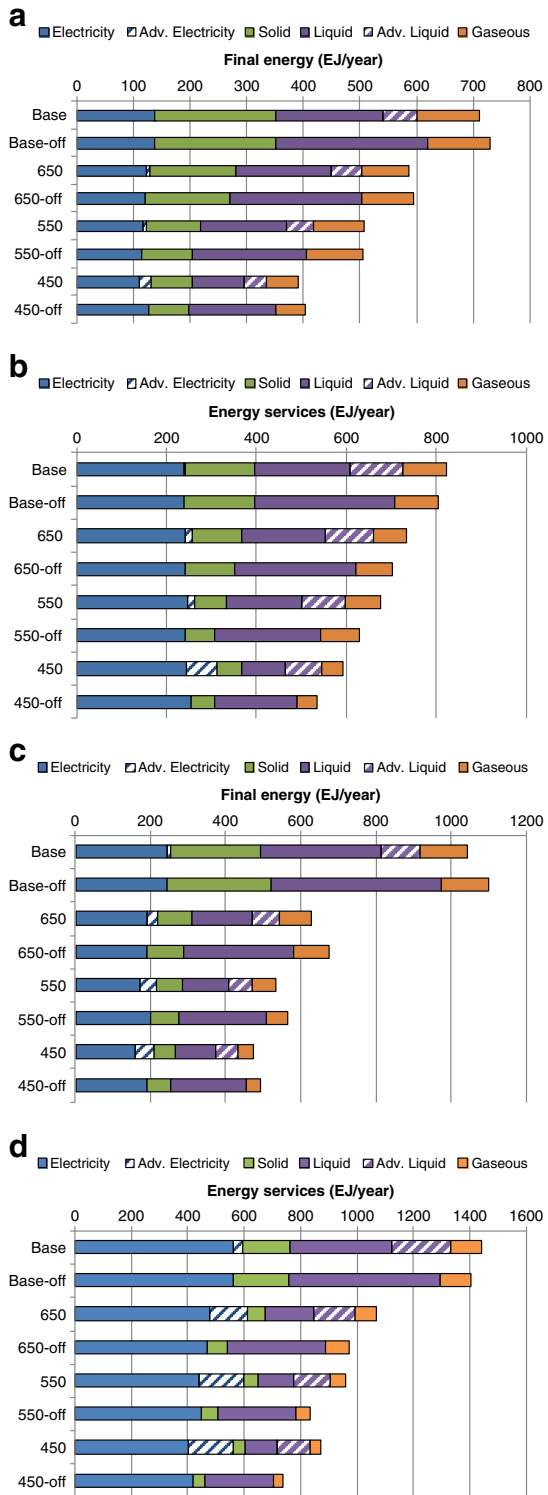
with GHG constraints in 2100 rise to 57 % in the 650 scenario, 63 % in the 550 scenario, and 65 % in the 450 scenario.

The electrification rates on based on energy services with GHG constraints and without the advanced end-use technologies are over 8 % lower than those with the advanced end-use technologies in 2100. The electrification rates are increased by the advanced electric end-use technologies. The combination of electrification and the advanced electric end-use technologies is a powerful option to achieve strict GHG constraints.

4 Conclusions

In this study, we have presented a new model called the BET (Basic Energy systems, Economy, Environment, and End-use Technology) model, which explicitly incorporates end-use technologies within a macroeconomic framework based on optimal growth theory. The BET model includes advanced end-use technologies such as industrial induction heaters, industrial heat-pump heaters, heat-pump water heaters in the residential and commercial sectors, road freight hybrid trucks, and road passenger electric vehicles. The BET model allows us to examine the role played by electrification and advanced end-use technologies to achieve a climate target in a more systematic fashion, ranging from changes in usage of end-use technologies to power generation mix.

Using the BET model, we have conducted simulations and obtained the following results.

(1) Turning off the advanced end-use technologies results in GDP losses, even in the scenario without GHG constraints. Such losses become larger with a more stringent climate policy. The model results suggest that the advanced end-use technologies are a promising way to contain GDP loss when the climate target is stringent.
(2) Advanced end-use technologies are important in reducing carbon prices, especially in the scenarios with stringent GHG constraints.
(3) Electricity demand is relatively stable, but non-electricity demand decreases as the GHG constraints become more stringent. This is because electricity can be supplied using various low-carbon options such as renewables, nuclear energy, and fossils with CCS.
(4) Electrification rates based on energy services are high under stringent GHG constraints. As the GHG constraints become stricter, advanced electric end-use technologies such as heat-pump water heaters play increasingly important roles in supplying energy services. The combination of electrification and advanced electric end-use technologies is a powerful method to achieve strict GHG constraints.

As the BET model is in the early stage of development, it has many deficiencies, necessitating further model development. The BET model does not include mitigation options for non-CO_2 GHGs. The model lacks backstop technologies for solids and liquids, although biomass solids and liquids are available (with resource constraints). These deficiencies might be one of the reasons for high carbon prices and GDP losses found in the 450 scenario, which warrant further investigation.

Another key problem is its treatment of energy efficiency barriers. It is well known that there are various barriers that prevent economically beneficial measures of energy efficiency, but such effects are not represented in the current configuration of the BET model. It is possible to use hurdle rates for end-use technologies to crudely incorporate aspects of

efficiency barriers. This is also left for future analysis (for a full list of topics of future work, see the ESM).

Though we explored the importance of end-use technologies by conducting sensitivity analyses, a more systematic approach is desired. The EMF27 has a systematic approach to mostly supply-side technologies. As a next step, it is our plan to systematically examine the value of various types of end-use technologies.

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