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Methane mitigation timelines to inform energy technology evaluation

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Abstract

Energy technologies emitting differing proportions of methane (CH_4) and carbon dioxide (CO_2) vary significantly in their relative climate impacts over time, due to the distinct atmospheric lifetimes and radiative efficiencies of the two gases. Standard technology comparisons using the global warming potential (GWP) with a fixed time horizon do not account for the timing of emissions in relation to climate policy goals. Here we develop a portfolio optimization model that incorporates changes in technology impacts based on the temporal proximity of emissions to a radiative forcing (RF) stabilization target. An optimal portfolio, maximizing allowed energy consumption while meeting the RF target, is obtained by year-wise minimization of the marginal RF impact in an intended stabilization year. The optimal portfolio calls for using certain higher-CH_4-emitting technologies prior to an optimal switching year, followed by CH_4-light technologies as the stabilization year approaches. We apply the model to evaluate transportation technology pairs and find that accounting for dynamic emissions impacts, in place of using the static GWP, can result in CH_4 mitigation timelines and technology transitions that allow for significantly greater energy consumption while meeting a climate policy target. The results can inform the forward-looking evaluation of energy technologies by engineers, private investors, and policy makers.

1. Introduction

Energy technologies emit greenhouse gases, primarily CO_2 and CH_4, with widely differing atmospheric lifetimes and radiative efficiencies [1]. The temporal proximity of these emissions to a climate policy threshold, such as a radiative forcing (RF) stabilization target, should factor into assessments of the climate impacts of energy technologies. This is because, in the presence of an RF stabilization policy [2, 3], the importance of mitigating more potent but shorter-lived greenhouse gases will increase as the build-up of forcing agents approaches the target level [4–7]. Standard technology evaluation does not account for the timing of emissions relative to a climate policy goal. The most commonly used method converts different greenhouse gases to their CO_2-equivalent mass values using the global warming potential (GWP(100)) emissions equivalency metric [8, 9], which compares gases by integrating their RF impacts over a fixed time horizon of 100 years. Despite scientific and economic critiques of the static GWP(100) (e.g. [10–16]), this metric is widely applied in forward-looking technology evaluation [17] and in climate change mitigation policy formulation [2, 18–21].

The dynamic climate impacts of technology adoption scenarios can be studied using integrated assessment models [22–27], which capture the interdependencies of gases that are co-emitted by various technologies in differing proportions [27, 28]. Models also demonstrate the benefits of mitigating short-lived climate forcings to reduce peak warming, and (in contrast to the benefits of immediate CO_2 reductions) find more limited benefits from early mitigation of these forcing agents [29, 30]. To be applied to technology evaluation, however, these insights must be translated from the level of the scenario or set of scenarios modeled (measuring total impact) to the level of technologies (measuring impact intensities, e.g. emissions per unit energy converted) [31, 32].

Given the advance planning needed for technology development, to support R&D and infrastructure investment, and the inherent uncertainties about the future scenario to be followed (e.g. energy demand, emissions pathways), these impact intensity estimates must be reasonably robust to a range of possible future scenarios.

In recognition of the need for simple tools to perform dynamic comparisons of emissions impacts, several emissions equivalency metrics have been proposed as dynamic alternatives to the GWP [33–40], based on instantaneous and integrated measures of temperature, RF, and economic impact. Questions remain about how beneficial these alternatives are, and whether they can be used to make technology comparisons that are robust to a range of future scenarios. Here we contribute to this debate by formulating a model to investigate optimal technology choice under an RF constraint, identifying the corresponding metric, and showing the benefits of applying this method to technology evaluation. We answer the following questions. Given the emissions intensities of candidate technologies, how much is gained by applying a dynamic metric (as compared to the static GWP)? Can a scenario-independent technology comparison be performed?

We represent dynamic technology choice as a simplified forward-looking multi-period portfolio optimization problem, maximizing energy consumption over a planning horizon in the presence of an RF stabilization constraint. This formulation leads naturally to an analytical expression for technology impact that changes over time based on the marginal RF impact in the stabilization year. The marginal RF impact can be determined for a range of scenarios leading to stabilization at a given target RF level (section S1). This formulation of the technology choice problem is equivalent to applying the instantaneous climate impact (ICI) emissions equivalency metric proposed in earlier work [40]. Here we demonstrate the sizable benefits of using this approach to plan for technology transitions given a global RF target. The resulting technology evaluation is robust to uncertainties in the stabilization year over a range of scenarios, as well as to uncertainties in future radiative efficiencies and the atmospheric lifetime of CH_4, under a 3 W m^{-2} RF target.

The optimal technology portfolio uses relatively CH_4-heavy technologies in earlier years, switching to relatively CH_4-light technologies as an intended RF stabilization year approaches. This switching portfolio facilitates significantly greater energy consumption than the exclusive use of either technology alone. These results suggest a role for CH_4-heavy technologies as 'bridges' to lower emissions intensity alternatives. The early use of the CH_4-heavy technology (the first listed in each pair) is optimal only if the stabilization horizon exceeds 22 years for compressed natural gas and gasoline, 14 years for algae biodiesel and electric vehicles, and 19 years for renewable natural gas and switchgrass ethanol. Given a stabilization horizon from the present to mid-century, the energy consumption gain from an optimal switching portfolio can be up to 15% and 50% compared to using only the CH_4-light or CH_4-heavy technology, respectively. The GWP(τ), in contrast, leads to a single, static technology portfolio, which for the GWP(100) results in either a significant overshoot of the stabilization target or, if constrained by the target (for example through a multi-basket emissions policy that addresses greenhouse gases separately), allows significantly lower energy consumption. The GWP(35) does not lead to an overshoot but results in lower energy consumption than the switching portfolio.

The main contributions of this paper are twofold. We show that the differences in the CH_4 and CO_2 emissions intensities of the transportation technologies examined are large enough that planning for technology transitions and CH_4 mitigation can yield significant returns, in terms of supporting energy consumption while meeting a climate policy target (here formulated around RF stabilization). We also develop a method for technology evaluation against climate policy targets that allows for an effective and relatively scenario-independent technology comparison, as described further in sections to follow.

2. Methods

In this section we describe the sectoral RF stabilization target (section 2.1), the evaluation of technology RF impacts (sections 2.2–2.3), and the technology portfolio optimization model (section 2.4).

2.1. RF stabilization constraints

Changing atmospheric concentrations of greenhouse gases are associated with changes in global mean temperature (with a time lag) and a range of impacts related to temperature or more directly to heat fluxes [41]. Climate change mitigation targets are commonly formulated around a recommended temperature threshold [3], from which an RF stabilization level can be derived. We use a 3 W m^{-2} global RF stabilization target, which in equilibrium is roughly equivalent to a 2 °C temperature change [1] from pre-industrial levels, a commonly cited climate target [3]. A range of scenarios stabilizing at this level is determined [40, 42], with stabilization occurring within a range of approximately 15 years up to 2050 (see section S1). A stabilization year of 2050, consistent with a 3 W m^{-2} RF target and the RCP2.6 scenario [43, 44], is used as an example but we also examine the effect of earlier stabilization years.

Beginning in the year 2015, the global RF target required for stabilization in 2050, computed by subtracting the estimated RF due to legacy emissions (pre-

2015 emissions remaining in the atmosphere in 2050) from 3 W m^{-2}, is found to be 1.6 W m^{-2} of which an estimated 70% or 1.12 W m^{-2} is attributable to global energy-related emissions [1]. In our model, the RF stabilization target for a specific energy sector is its fraction of the global energy-related RF target in proportion to its energy consumption today relative to total global energy consumption. The US road transportation sector constitutes about 4% of today's global primary energy consumption [45]. We consider as an example 36% of the US road transportation sector for our technology portfolio choice and an RF stabilization target (TRF) for this subsector of 1% of the global stabilization target, or 0.016 W m^{-2}. The benefits of planning for CH_4 mitigation would apply to larger energy end-use sectors as well. (The effect on our results of deviating from this particular sectoral RF target is discussed in section 3.3.)

2.2. Marginal RF and GWP calculations

Technologies emit multiple greenhouse gases, the three most significant being CO_2, CH_4 and nitrous oxide (N_2O), indexed by $i = K, M, N$, respectively. The RF following the use of a technology can be linearly approximated by a function of the emission intensities of these gases, and their radiative efficiencies and atmospheric lifetimes [1]. However, in sections 3.3 and S10 the effects of variable gas lifetimes and nonlinearities in this relationship, due to the effect of changing background greenhouse gas concentrations on marginal RF, are studied [46]. Let b_{ij} denote the mass of gas i emitted by technology j per unit energy consumption, A_i the radiative efficiency of gas i, and $f_i(t, t')$ the impulse response function representing the fraction of gas i retained in the atmosphere at time t following emission at time t',

$$f_i(t, t') = \exp\left(-\frac{t - t'}{\tau_i}\right), \text{ for } i = M, N, \quad (1)$$

$$f_K(t, t') = a_0 + \sum_{k=1}^{3} a_k \cdot \exp\left(-\frac{t - t'}{\tau_k}\right). \quad (2)$$

Empirical values of A_i and the parameters in $f_i(t, t')$ for CO_2, CH_4 and N_2O [1] are given in section S2.

The instantaneous RF from unit energy consumption using technology j is $\sum_i b_{ij} A_i$ and the RF impact at evaluation time t of a pulse emission from unit energy consumption using technology j at emission time t' is

$$\mathrm{RF}_j(t, t') = \sum_i b_{ij} A_i f_i(t, t'). \quad (3)$$

For sustained emissions occurring over time, prior to the evaluation time t, $\mathrm{RF}_j(t, t')$ in (3) represents the marginal RF impact at t of unit energy consumption at emission time t'. This corresponds to the absolute ICI metric [40] for technology j (see section S5).

Using the same parameters, technology j's impact based on the GWP(τ), is

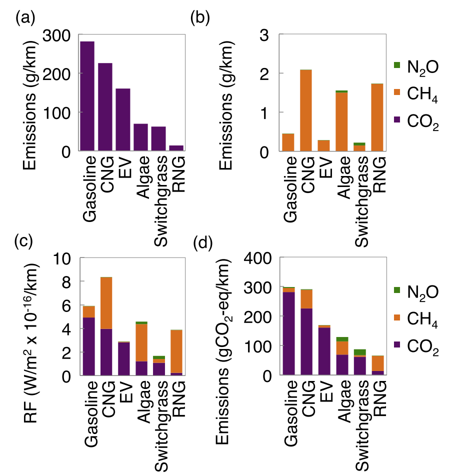

Figure 1. Life cycle technology greenhouse gas emissions per kilometer traveled. (a) Grams CO_2 emitted per kilometer traveled. (b) Grams CH_4 and N_2O emitted per kilometer traveled. (c) Instantaneous radiative forcing. (d) Grams CO_2-equivalent per kilometer using GWP(100) for each technology. Technologies vary in the composition of their emissions. Gasoline, electric vehicles using the current US electricity mix (EV), and an 85% switchgrass ethanol blend with gasoline (switchgrass) are CH_4-light and compressed natural gas (CNG), algae biodiesel (algae), and landfill renewable natural gas (RNG), all with CH_4 leakage, are CH_4-heavy. (Data source: GREET 2013.)

$$\mathrm{GWP}_j(\tau) = \sum_i b_{ij} \mathrm{GWP}_i(\tau), \quad (4)$$

in grams CO_2-equivalent per unit energy consumption, where

$$\mathrm{GWP}_i(\tau) = \frac{\int_{t'}^{t'+\tau} A_i f_i(t'', t') \mathrm{d}t''}{\int_{t'}^{t'+\tau} A_K f_K(t'', t') \mathrm{d}t''} \quad (5)$$

and τ is the integration horizon.

2.3. Description of technologies

Life cycle emissions intensities b_{ij} are obtained from the GREET model (https://greet.es.anl.gov) for three pairs of transportation technologies, where 'technology' refers to the combined fuel and vehicle jointly. Emissions intensities are current estimates for the US, and values may vary geographically and over time. Significant reductions in CH_4 emissions may be possible [47]. The sensitivity of our results to such variations is discussed in section 3.3.

For each technology pair the CH_4-heavy h and CH_4-light l are chosen so that $b_{Mh} > b_{Ml}$ (figures 1(a) and (b)). CH_4-heavy technologies compressed natural gas (CNG), algae biodiesel (algae), and renewable natural gas (RNG) exhibit higher instantaneous RF than their CH_4-light counterparts gasoline, electric vehicle (EV), and switchgrass ethanol (switchgrass) (figure 1(c)) but lower GWP(100)-based impacts (figure 1(d)), due to the higher

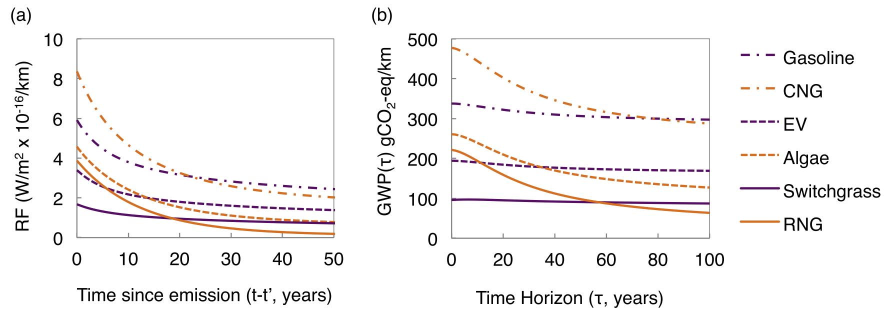

Figure 2. Radiative forcing (RF) and global warming potential (GWP) of technology emissions. (a) RF over time resulting from use of a technology (see (3)). (b) GWP over integration horizon τ resulting from use of a technology (see (4)). Purple represents CH_4-light fuels: gasoline, electric vehicles (EV), and 85% switchgrass ethanol blend (switchgrass). Orange represents CH_4-heavy fuels: compressed natural gas (CNG), algae biodiesel (algae), and landfill renewable natural gas (RNG). Fuels with similar GWP(35) values are presented in pairs, with solid, dashed, or dotted–dashed lines.

radiative efficiency but faster decay time of CH_4 relative to CO_2. See table S3 for numerical values associated with figures 1(a)–(d).

Since CH_4 decays much faster than CO_2 (and N_2O), the RF induced by an initial pulse emission from a CH_4-heavy technology falls faster with t and its GWP(τ) falls faster with τ than from its CH_4-light counterpart (figures 2(a) and (b)). The initial values in figure 2(a) correspond to the bars in figure 1(c), and the GWP(τ) values at $\tau = 100$ in figure 2(b) correspond to the bars in figure 1(d). To the extent possible, technologies in each pair are matched in terms of their GWP(35) impact values, where 35 years is the stabilization horizon between 2015 and 2050.

2.4. Technology portfolio optimization model

Energy technologies emit greenhouse gases as sustained streams over time rather than as a single pulse. We use a discrete time approximation of energy consumption where emissions occur as a pulse at the end of each year $t' = 0, \ldots, t_S$.

Let $c_{t'}$ denote energy demand in year t' and $x_{jt'}$ the fraction of $c_{t'}$ supplied by technology j in year t'. A technology portfolio p is defined by the set $x_{jt'}$ over time $t' = 0, \ldots, t_S$, and $\mathrm{RF}_p(t_S)$ denotes the total RF induced by the portfolio at the end of the stabilization year t_S. In the model presented here, the technology planning horizon coincides with the RF stabilization year, given the concurrence of commonly suggested stabilization horizons [43, 48] and timelines for technology development and infrastructure planning [49]. However, the model could be adapted to cases where the planning and stabilization horizons differ (see section S6.1). The optimization model that selects a technology portfolio and energy consumption levels to maximize total consumption, while satisfying the RF target in the stabilization year, is given below.

Optimization model

$$\begin{aligned} &\max_{c_{t'}, x_{jt'} \forall j, t'} \quad \sum_{t'=0}^{t_S} c_{t'} \\ &\text{s.t.} \quad c_{t'} = c_{t'-1}\left(1 + g_{t'}\right) \text{ for } 1 \leqslant t' \leqslant t_S, \\ &\qquad \mathrm{RF}_p\left(t_S\right) \leqslant \mathrm{TRF}, \\ &\qquad x_{jt'} \in [0, 1] \text{ and } \sum_j x_{jt'} = 1, \\ &\qquad\quad \text{for } j = h, l \text{ and } 0 \leqslant t' \leqslant t_S, \end{aligned}$$

where the objective function represents total energy consumption, the first constraint defines the energy consumption profile based on growth rate $g_{t'}$ in year t' and the second constraint ensures that RF does not exceed the target (TRF) in the stabilization year.

The portfolio contribution to RF, given by $\mathrm{RF}_p(t_S)$, is

$$\mathrm{RF}_p\left(t_S\right) = \sum_{t'=0}^{t_S} c_{t'} \sum_j x_{jt'} \mathrm{RF}_j\left(t_S, t'\right). \qquad (6)$$

$\mathrm{RF}_p(t_S)$ is the sum of RF impacts in the stabilization year of all prior portfolio emissions. $\mathrm{RF}_j(t_S, t')$ represents the marginal RF impact of unit energy consumption using technology j in emission year t'. Using (6) in the model simplifies its solution as we can first determine the optimal technology choice in each year by minimizing $\mathrm{RF}_p(t_S)$ and then maximize energy consumption using the optimal portfolio.

Since the model constrains RF only in the stabilization year, TRF overshoots are possible. An additional set of constraints

$$\mathrm{RF}_p(t) \leqslant \mathrm{TRF} \text{ for } 0 < t < t_S, \qquad (7)$$

(referred to as overshoot constraints) are also presented to assess the impact of overshoot restrictions on optimal energy consumption levels. Overshoots could be restricted through policies that separately cap short- and long-lived greenhouse gases [5].

The model is applied to the three transportation technology pairs shown in figure 1. We consider annual energy consumption growth rates of 0%, representing flat consumption. (In section S6.2, we also consider how the results change under an energy consumption growth rate of 1.2% [45].) Additionally, we consider the effect of uncertainty in the stabilization horizon (see section S9), based on a 15 year range of stabilization years given a plausible set of emissions scenarios for stabilizing RF at 3 W m^{-2} (see section 3.3 and section S1).

2.5. Portfolio optimization with the GWP

We compare the optimal technology portfolio based on the dynamic emissions impact evaluation, with the portfolio (and energy consumption) that would be obtained using the GWP. This allows us to estimate the gains of this approach over the standard GWP-based method for technology evaluation. CO_2-equivalent emissions are determined using the GWP and treated as CO_2 when evaluating the RF impact in the stabilization year. (This is similar to the approach outlined above but uses the GWP in place of a marginal RF impact based metric.) Therefore, the GWP-based estimate of RF impact in the stabilization year of technology j per unit energy consumption in year t' is $\mathrm{GWP}_j(\tau) A_K f_K(t_S, t')$, where $\mathrm{GWP}_j(\tau)$ is given by (4) (in units CO_2-equivalent per unit energy consumption), A_K is the radiative efficiency of CO_2, and $f_K(t_S, t')$ is the fraction of CO_2 emitted at time t' remaining in the atmosphere at time t_S. Using this definition, the intended RF in year t_S, based on the GWP, of using technology portfolio p for the energy consumption stream $c_0, \ldots, c_{t_S}$, is

$$\mathrm{RF}_p^g\left(t_S\right) = \sum_{t'=0}^{t_S} c_{t'} \sum_j x_{jt'} \mathrm{GWP}_j(\tau) A_K f_K\left(t_S, t'\right). \quad (8)$$

Equation (8) is used in the optimization model in place of $\mathrm{RF}_p(t_S)$ given in (6) to determine the maximum energy consumption allowed by the GWP-based portfolio. We consider both GWP(100) and GWP(35) in our numerical simulations: GWP(100) because it is the most widely used metric and GWP(35) because it is consistent with our planning horizon of 35 years.

3. Results

The solutions to the technology portfolio optimization model are described in section 3.1 where we investigate the benefits of planning for CH_4 mitigation. Section 3.2 describes the optimal solutions calculated using the GWP. Section 3.3 presents a sensitivity analysis.

3.1. Optimal portfolio based on dynamic emissions impact evaluation

The optimal technology portfolio is determined by year-wise minimization of $\mathrm{RF}_j(t_S, t')$ across technologies, which can yield a technology portfolio switching from the CH_4-heavy to the CH_4-light technology in an optimal switching year t^*. The maximum possible energy consumption is determined using the optimal technology portfolio. The results support the use of suitable CH_4-heavy technologies as bridging technologies, if the stabilization horizon is sufficiently long, i.e. t^* exists and has not already passed. All three technology pairs shown in figure 1 satisfy these conditions. The marginal RF impact resulting from using each technology over time, in an example stabilization year of 2050, is shown in figure 3. The general solution to the optimal portfolio problem is given in sections S6.1 and S6.2.

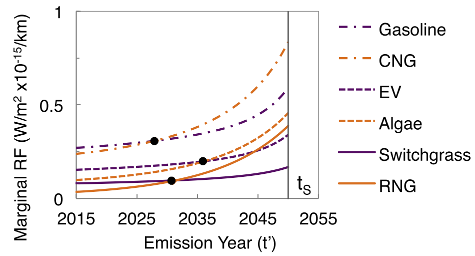

Figure 3. Marginal RF impact at the time of stabilization (t_S) of technology use at different emission times t' ($\mathrm{RF}_j(t_S, t')$ on the right hand side of (6)). Pair-wise comparisons are presented for gasoline and compressed natural gas (CNG), electric vehicle (EV) and algae biodiesel (algae), and 85% switchgrass ethanol blend (switchgrass) and landfill renewable natural gas (RNG), with corresponding switching horizons of 13, 21, and 16 years indicated by black dots.

The optimal switching-to-stabilization time span is 22 years for CNG and gasoline, 14 years for algae and EV, and 19 years for RNG and switchgrass. Using a stabilization horizon of 35 years (2015–2050), it is optimal to use CNG for 13 years, algae for 21 years, and RNG for 16 years, followed by a switch to gasoline, EV, and switchgrass, respectively. If the stabilization year is shifted up to 2043 (the middle of the modeled range of years discussed in section 2.1), the optimal switching year for each technology pair shifts by 7 years, keeping the same time span between switching and stabilization (see section S9).

We calculate the maximum allowed gasoline-equivalent energy consumption for individual technologies in each technology pair and compare the values to the consumption using the optimal switching portfolio (figure 4). The optimal switching portfolio increases the allowed energy consumption relative to each individual technology alone. The percentage energy consumption gains relative to the individual CH_4-light and CH_4-heavy technologies are shown in figures 4(b) and (c), respectively.

The results call into question the benefits of CNG at current CH_4 leakage estimates, given the relatively small gain of 2% using a switching portfolio (from CNG to gasoline) over using gasoline alone, and the dominance of gasoline-based vehicles and infrastructure today. The investment required to make the transition to CNG may not be justified by the modest gains in energy consumption. Furthermore, the results demonstrate the higher energy consumption supported by the lower emissions technologies (EV, algae

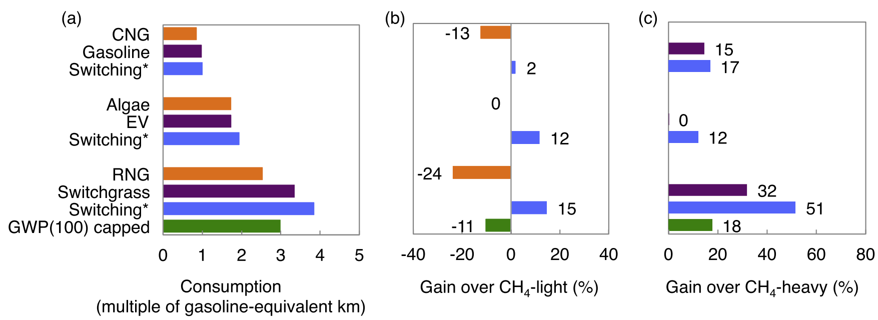

Figure 4. Optimal energy consumption over the stabilization horizon that meets the target RF level at the stabilization time. (a) Total consumption for the three technology pairs (as a multiple of travel distance supported by gasoline): gasoline and compressed natural gas (CNG), electric vehicles (EV) and algae biodiesel (algae), and 85% switchgrass ethanol blend (switchgrass) and landfill renewable natural gas (RNG). (b) Percentage gain in energy consumption over the CH_4-light (purple) technology. (c) Percentage gain over the CH_4-heavy technology (orange). Switching portfolios (blue) involve a transition from a CH_4-heavy to a CH_4-light technology. The GWP(100) capped portfolio (green) selects the CH_4-heavy technology and approximates a case in which different gases are regulated with separate policies, a 'multi-basket' approach, thereby avoiding an overshoot. Applying the GWP(35) results in the selection of the CH_4-light technology (purple) and corresponding energy consumption level.

and switchgrass, RNG). The CNG, gasoline pair does not meet projected energy demand under this RF target.

The RF trajectories for individual technologies in each pair, and their optimal switching portfolios, are shown in figures 5(a)–(c). While the RF constraint is met in the stabilization year, the RNG-switchgrass optimal switching portfolio exhibits limited overshoots prior to the stabilization year, peaking at approximately 11% above the sector RF target (0.1% of the global target) in the switching year. Early overshoots can be concerning if they are relatively large and long-lasting, and if policy targets are set to be consistent with climate system thresholds above which abrupt climate changes may occur [50, 51].

An early RF overshoot can occur with a switching portfolio if the CH_4-heavy technology has a sufficiently high CH_4 intensity relative to the CH_4-light technology (if the percent difference is significantly large). Early consumption using a CH_4-heavy technology can in this case lead to an increase in RF followed by a rapid decrease after switching, resulting in a switching year 'peak' RF that exceeds the RF constraint. This effect is observed for the RNG-switchgrass portfolio, whereas the CNG-gasoline and algae-EV portfolios do not result in an RF overshoot (figure 5). See section S6.4.

Overshoots can be avoided by choosing an earlier stabilization year (if averse to the risk of a temporary overshoot) (figure S7). Overshoots could also be restricted in a policy context where gases are capped separately. A 'multi-basket' policy could be formulated to achieve an overshoot restriction. In this case planning to transition from a CH_4-heavy to a CH_4-light technology still provides an advantage over applying the GWP, as the switching portfolio will allow greater energy consumption while meeting the RF constraint (see figure 4(a) and section S8).

3.2. Optimal portfolio based on the GWP

The GWP-based optimal technology portfolio is determined by using the intended RF based on GWP (τ) from (8) instead of (6) in the technology portfolio optimization model (see section S7 for the general solution and proof). Using the GWP(100), the CH_4-heavy technologies in each pair are used to satisfy the entire portfolio, since they have lower GWP(100)-evaluated impacts than their CH_4-light counterparts (figure 2(b) at $\tau = 100$). The GWP(100)-based intended RF underestimates actual RF in the stabilization year, thus allowing higher energy consumption and overshooting the RF target (black lines in figure 5). If instead the RF constraint is forced to be met, the allowed energy consumption can be much lower when applying the GWP for technology evaluation than when planning for a switching portfolio (20% lower using the GWP(100) with a cap versus the RNG-switchgrass portfolio, figure 4 and section S8).

Since the CH_4-light technology has a lower GWP (35) than its CH_4-heavy counterpart for each technology pair (figure 2(b) at $\tau = 35$), the CH_4-light technology is selected over the entire horizon when the GWP(35) is applied. Because the integration horizon is the same as the stabilization horizon, the GWP(35)-based intended RF is consistent with the actual RF. Therefore, the maximum energy consumption allowed by the GWP(35) (using equation (8)) is the same as that allowed by the CH_4-light technologies (equation (6)) while meeting the RF target (figure 4, dashed grey lines in figure 5). The switching portfolio can support greater energy consumption than the GWP(35)-based selection of the CH_4-light technology alone. The RNG-switchgrass portfolio allows a 15% energy gain over switchgrass alone. The algae-EV portfolio allows a 12% gain over EV alone, and CNG-gasoline allows for a 2% gain over gasoline alone. See figure 4(b) and section S7.

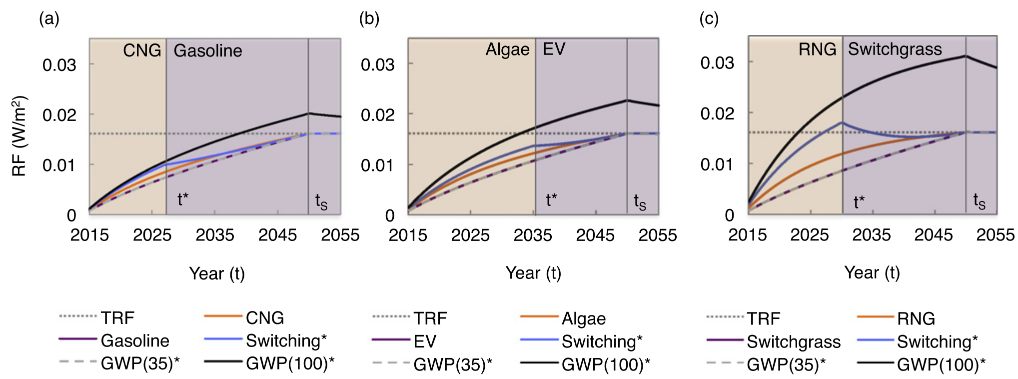

Figure 5. Radiative forcing (RF) resulting from technology portfolios using marginal RF and the GWP(100) to evaluate impacts. (a) Gasoline and compressed natural gas (CNG) portfolios. (b) Electric vehicle (EV) and algae biodiesel (algae) portfolios. (c) 85% switchgrass ethanol blend (switchgrass) and landfill renewable natural gas (RNG) portfolios. Switching portfolios (blue) outperform portfolios relying on CH_4-light (purple) or CH_4-heavy (orange) fuels alone, in that they allow greater energy consumption while avoiding a significant overshoot of the sector RF target (TRF). Optimal technology choice using the GWP(100) to select the technology and energy consumption level (black) exhibits a target overshoot over a wide range of years. Using the GWP(35) to select the optimal technology portfolio results in the selection of the CH_4-light technologies (gasoline, EV and switchgrass) and leads to no RF target overshoots (dashed black) and less energy consumption than the corresponding switching portfolio. (t^*, optimal switching year; t_S, stabilization year).

The energy gains of the switching portfolio over using the CH_4-light technology alone are determined by the percent difference in CH_4 intensities of the CH_4-heavy and CH_4-light technologies. The percent energy gains of the dynamic evaluation method can be larger if this difference is greater (as long as the difference is not so large that the CH_4-heavy technology is no longer selected over the CH_4-light technology). See figure 4 and section S7.

3.3. Robustness of results

Here we discuss the robustness of the results presented to uncertainties in the stabilization year, the radiative efficiencies and lifetimes of greenhouse gases, and the sectoral RF target. We find that the benefits of technology transition portfolios are relatively robust to these uncertainties, suggesting the utility of this approach to technology evaluation (given a 3 W m^{-2} global RF stabilization target) despite an inherent lack of knowledge about the future. We also discuss how the insights from this research apply given changing emissions intensities of technologies, variable technology costs and quality of service, and alternative global RF stabilization targets.

Sensitivity to stabilization year uncertainty. We compare the optimal decisions based on a plausible range of stabilization horizons for a 3 W m^{-2} RF target (section S1). Examining the stochastic case, where technologies are evaluated based on the expected stabilization year (2043) but actual stabilization may occur earlier or later in the range 2035–2050, the switching portfolio still outperforms other portfolios (CH_4-light/GWP(35), CH_4-heavy, capped GWP (100)), with the energy consumption gains of the switching portfolio only modestly reduced. Stabilization year uncertainty can reduce the energy consumption gains (in gasoline-equivalent km) of the switching portfolios by 4%–6%. See table S9. Therefore, for these technology pairs, the performance of an optimal portfolio is relatively insensitive to uncertainty in the stabilization year.

Sensitivity to a changing background concentration of greenhouse gases. We test the robustness of the gains of the dynamic emissions evaluation model over the static GWP, given that the radiative efficiencies of CO_2, CH_4, and N_2O and the lifetime of CH_4 are likely to vary over time as the background concentrations of greenhouse gases change. To test the sensitivity of our results to these changes we select the RCP2.6 [44] as a sample scenario. (The RCP2.6 is just one possible 3 W m^{-2}-compliant scenario but is reasonable for demonstrating the rough scale of the effect of changing radiative efficiencies and CH_4 lifetimes.)

We find that the results are robust to changing radiative efficiencies and a changing CH_4 lifetime. If technology switching decisions are made using the assumptions of constant radiative efficiency and CH_4 lifetime (representing the forward-looking part of the model), but energy consumption and RF scenarios are determined based on a changing radiative efficiency and a variable lifetime (representing the realized outcome), the gains of the switching portfolios are preserved. Specifically, the gains over the CH_4-heavy (CH_4-light) technology are 17% (4%) for CNG-gasoline, 15% (16%) for algae-EV and 56% (25%) for RNG-switchgrass. This is compared to gains of 17% (2%), 12% (12%), and 51% (15%), respectively, under the constant radiative efficiency case. See section S10, figures S11 and S12. We further examine the impact of other scenarios where greenhouse gas emissions and concentrations continue to increase over time (namely, RCP6 and RCP8.5) and find that the gains of the switching portfolio over the CH_4-light and CH_4-heavy technologies are comparable to the results shown for RCP2.6. See section S10.

Sensitivity to sectoral RF target. Variations in the fraction of the global RF target allocated to a given sector would change the energy consumption levels in our numerical analysis, but would not affect the technology transition (or CH_4 mitigation) timeline in the optimal portfolio. (The change in energy consumption due to a change in the RF target can be inferred from equation (S11) in proposition S2. The optimal switching timeline is unaffected as equation (S6) is independent of the RF target. See sections S6.2 and S6.1, respectively.)

Effect of variable emissions intensities. CH_4 intensities depend on venting and leakage in the production or supply infrastructure and are expected to vary across geographical locations and over time. Significant reductions may be possible [47]. If the CH_4 emissions intensity of the CH_4-heavy technologies decreases, as compared to the current US estimates on which the results are based , switching will move closer to the intended stabilization year up to a point where switching is no longer optimal. We can estimate how significant these CH_4-emissions intensity reductions would need to be to make switching suboptimal. Holding other emissions intensities constant, if the CH_4 emissions intensity of CNG decreases by 73% or greater, switching to gasoline is no longer optimal. Reductions of the algae (RNG) CH_4 emissions intensity of 46% (66%) would make switching to EV (switchgrass) suboptimal. See section S6.5.

Effect of technology costs or quality of service. The model is constructed to determine whether a dynamic emissions impact evaluation can yield significant gains, not to represent an expected outcome scenario in the real marketplace. The numerical results we present would only hold in the marketplace (with the lowest emissions technology pair representing the optimal portfolio) if technology costs and service level were comparable, energy consumption were equated to economic benefit, and the technologies examined represented the full range of options available. Although these conditions are not met, the model demonstrates the potential for substantial energy consumption gains (and associated economic benefits) from a dynamic emissions impact evaluation for planning technology switching or CH_4 mitigation, under a single- or multi-basket emissions cap. The dynamic emissions impacts we quantify are one important input into technology decisions in the marketplace under a climate policy, but the transition timelines and choice between technology pairs would also depend on the relative costs and service limitations of technologies (e.g. EV range constraints), as well as the benefits of the energy services provided.

Effect of alternative global RF stabilization targets. For stabilization horizons stretching, for example, to 2100 either due to changes in assumptions regarding the range of plausible emissions reduction rates or higher RF stabilization levels, the results presented here would change, with CH_4-heavy technologies favored for a longer period of time. In this case, the instantaneous measure of RF impact in the stabilization year could result in substantial RF overshoots in earlier years, making the emissions and technology evaluation approach described here less attractive. We note that century scale horizons are longer than practical for technology planning, and are therefore outside the scope of this paper. Furthermore, planning for an earlier-than-realized stabilization year would reduce the risk of RF overshoots.

4. Conclusion and discussion

In this paper we focus on dynamic technology evaluation and choice to meet a given RF stabilization level. We show that the optimal choice can be a technology switching portfolio, where a more CH_4-heavy technology is used initially, followed by a switch to a CH_4-light option. Such a switching portfolio can allow greater energy consumption than the exclusive use of either technology. These results support the case for using appropriate CH_4-heavy bridging technologies, given a sufficiently long stabilization horizon, but also caution against using CH_4-heavy technologies too close to the stabilization time-frame. We note that the same benefits would apply to planning for reducing CH_4 leakage from technologies that are currently CH_4-heavy but show potential for decreasing CH_4 emissions [52, 53]. This result points to two options: transitioning to low-CH_4 technologies or mitigating CH_4 emissions.

The model demonstrates the benefits, as compared to the static GWP(τ), of planning for technology transitions using a dynamic emissions impact evaluation approach or the ICI metric [40]. A switching portfolio can allow greater energy consumption than the GWP(35)-selected, CH_4-light technology (up to 15% for the technology examples studied), while still meeting the RF target. The GWP(100)-based portfolio allows even greater energy consumption but can lead to a significant overshoot of the intended RF stabilization level. If an RF constraint is applied exogenously, a situation which approximates the real-world case of a multi-basket emissions policy that regulates different gases through separate caps, the GWP(100)-based selection allows less energy consumption than the technology switching portfolio (up to 20% less for the technology examples studied).

The technology evaluation approach we develop is designed to be robust to uncertainty regarding the stabilization scenario but does require specification of a global RF stabilization target. Given a stabilization level, a range of stabilization years is determined, and the optimal year for switching from a CH_4-heavy to a CH_4-light technology is well-defined by this range. The optimal switching year does not depend on the future energy consumption level, and the benefits of technology switching will apply across a wide range of possible energy consumption scenarios. This robustness is important because there is a critical need for technology evaluation tools that perform well despite inherent uncertainty about the future, in order to inform technology design, private investment decisions, and policy development. These tools should also be transparent and easy to use and yet, to perform well, should incorporate broader climate policy goals.

We present such an approach here, to inform technology development timelines. Such planning can help direct efforts to reduce the costs of low emissions intensity technologies [31, 54–56]. Private actors investing in R&D and technology production capacity might use the insights on CH_4 mitigation timelines to decide which technology designs to invest in. Public actors might use the results to evaluate projects for R&D funding, considering likely technology-to-market development timelines and CH_4 leakage rates. The results also point to the importance of incorporating dynamic emissions impacts or multi-basket emissions caps into emissions regulations, to avoid the potential RF overshoots resulting from applying the GWP(100). US EPA regulations on power plants [19, 20], and other current and proposed policies [18, 21, 32], rely on the GWP(100) to evaluate technology impacts—or do not account for the impacts of non-CO_2 greenhouse gases at all. Methods like the one we propose can inform the formulation of policies to meet the demand for energy while also meeting climate change mitigation goals.

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