Secondary Energy Based Mitigation shares.

Supplementary Material for the Paper
"Asia's Role in Mitigating Climate Change:
A Technology and Sector Specific Analysis with ReMIND-R"

Gunnar Luderer, Robert C. Pietzcker, Elmar Kriegler,
Markus Haller, Nicolas Bauer

This document provides supplementary information on the abovementioned article. It contains a detailed description of the approach used to calculate mitigation shares and proofs that the approach is complete in the sense that the sum of all individual shares is equal to the difference between baseline and policy emissions.

1 Basic concept

The basic rationale is to attribute emission reductions induced by climate policy to individual technologies by tracking the substitution between different technology pathways for the provision of secondary energy. By considering region, time period, and secondary energy type individually, the calculation is performed at the highest possible resolution represented in the ReMIND model.

More formally, we base our method on the following requirements, or *axioms*:

(A1) The sum of all individual technology shares shall equal the difference between baseline and policy emissions for each time step and region.

(A2) For each time step, region and secondary energy carrier, the abatement credit (i.e., the emission intensity per unit of secondary energy production capacity replaced relative to baseline) shall be equal for all technologies with deployment levels higher than in the baseline.

(A3) For each time step, region and secondary energy carrier, the abatement credit for reductions of end-use shall be equal to that of secondary energy producing technologies.

(A4) For each time step and region, the mitigation share of technologies with deployment levels lower than in the baseline shall be zero.

These axioms are rather intuitive. (A1) demands that the decomposition of emissions abatement into shares be complete. (A2) and (A3) ensure that all technologies that produce the same secondary energy carrier as well as end-use efficiency are credited equal for the replacement of CO2-emitting production capacities that would have existed in the baseline. Axiom (A4) ensures that none of the emission reductions are attributed to "dirty" technologies for being deployed at lower levels than in the baseline.

2 Algorithmic Implementation

Based on the above axioms, secondary-energy based mitigation shares can be constructed in a straight-forward way. It is essential that the method is applied for each time step and region individually. However, for the sake of better readability the indices for region r and time t are omitted in the following. The routine is composed of the following distinct steps:

1. For each technology i and secondary energy type j, calculate the difference of production between baseline and policy scenario ΔS_{ij}:

$$\Delta S_{ij} = S_{ij}^{\mathrm{pol}} - S_{ij}^{\mathrm{bau}} \tag{1}$$

2. Calculate emission intensities for each technology i producing secondary energy carrier j:

$$\varepsilon_{ij}^{\mathrm{bau,pol}} = \frac{E_{ij}}{S_{ij}} \tag{2}$$

   In the case of joint production, emissions for each technology are distributed across products according to the relative output shares. Note that the emission intensities in the policy case can be different from those in the baseline, e.g. due to climate-policy induced efficiency improvements or different vintage structures.

3. Calculate abatement credit $\overline{\varepsilon}_j$ as the average emission intensity of replaced production capacities of secondary energy carrier j:

$$\overline{\varepsilon}_j = \frac{\sum_{i:\Delta S_{ij} \leq 0} (E_{ij}^{\mathrm{pol}} - E_{ij}^{\mathrm{bau}})}{\sum_{i:\Delta S_{ij} \leq 0} \Delta S_{ij}} \tag{3}$$

   where the sums run over all technologies with deployment ΔS_{ij} lower than in the baseline. We show in Sec. 4 that this definition of $\overline{\varepsilon}_j$ ensures that axiom (A1) is satisfied – i.e. that the sum of all individual technology shares equals the difference between baseline and policy emissions.

4. For all conversion technologies i that are deployed at higher levels than in the baseline, calculate mitigation contribution M_{ij} for the production of secondary energy carrier j:

$$M_{ij} = \begin{cases} \Delta S_{ij}(\overline{\varepsilon}_j - \varepsilon_{ij}^{\mathrm{pol}}) + S_{ij}^{\mathrm{bau}}(\varepsilon_{ij}^{\mathrm{bau}} - \varepsilon_{ij}^{\mathrm{pol}}) & \text{if } \Delta S_{ij} > 0 \\ 0 & \text{if } \Delta S_{ij} \leq 0 \end{cases} \tag{4}$$

The mitigation contribution is set to zero for technologies with deployment lower than in the baseline. Note that the second component in the sum accounts for changes in the emission intensity of the conversion technology. If the emission intensity is invariant between BAU and policy case, this term vanishes. This is usually the case, since climate policy will result in expansion of low emission technologies.

5. For each secondary energy carrier j, calculate the contribution of adjustments in energy end-use to emission reductions. These terms capture both the reductions in final energy demand and substitutions between end-energy carriers.

$$M_j^{\mathrm{end}} = -\sum_i (S_{ij}^{\mathrm{pol}} - S_{ij}^{\mathrm{bau}})\,\bar{\varepsilon}_j \tag{5}$$

Note that M_j^{end} can become negative if the secondary energy demand j is higher in the policy case than in the baseline. For some of the scenarios considered, we find electrification of energy end use to result in higher electricity consumption than in the baseline, thus yielding a negative end-use share for electricity. In line with intuition, however, this is found to be smaller than the end-use related emission reduction from non-electric end use.

3 Aggregation to sector shares

In the model setting discussed in the paper, the concept described in Sec. 2 results in about 450 mitigation contribution time series M_{ij} – one for each technology and region, plus one end-use share for each energy carrier and region. Fig. 1 gives a graphical representation of these *micro shares.*

The micro shares can be further aggregated across regions, end-use sectors, or technology groups (see Fig. 2). Table 1 shows the composition of the technology groups and their contribution to different end-use sectors. Note that the assignment to technology groups is complete; all conventional technologies are part of the *Fuel Switch* group and have a mitigation contribution unequal to zero if they are deployed at higher levels than in the baseline.

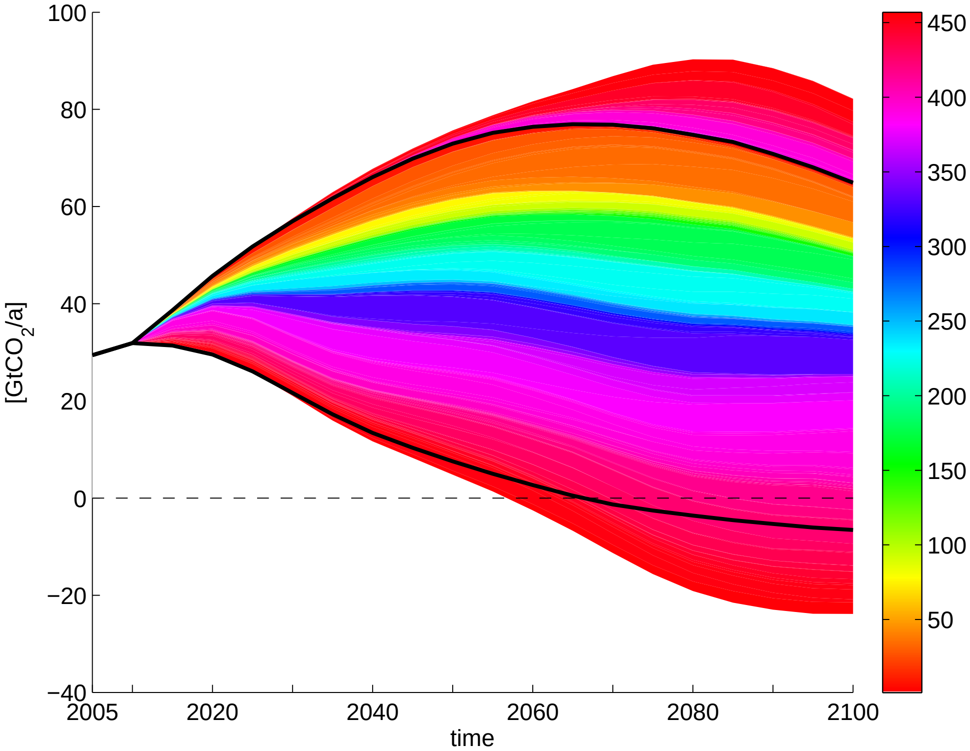


Figure 1: Micro shares: One technology share for each mitigation technology and region, plus one efficiency share for each secondary energy carrier and region, results in a total of about 450 shares.

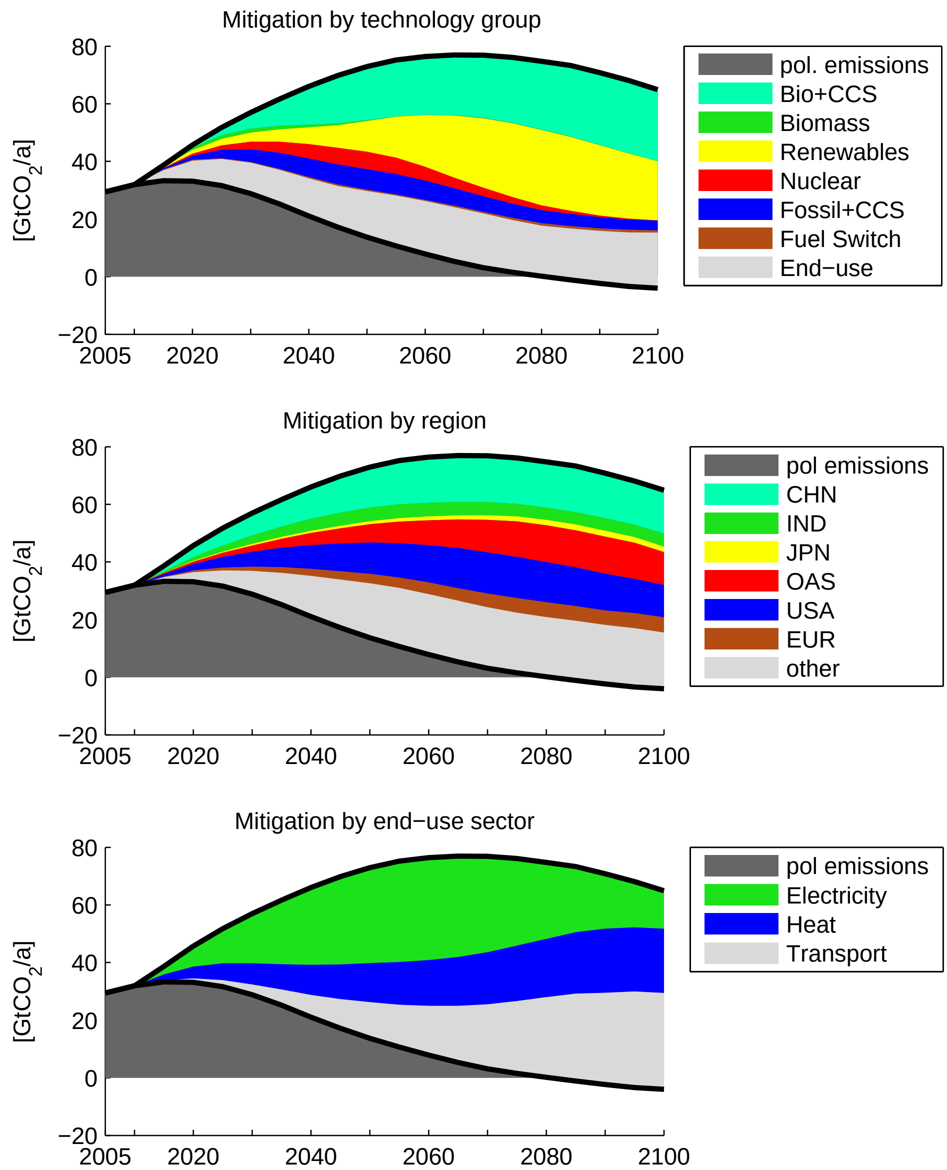


Figure 2: Aggregation of micro shares across technology groups, regions and end-use sectors.

Table 1: Technology groups and their contribution to end-use sectors. PP: power plant, CHP: combined heat and power, CC: combined cycle, IGCC: integrated gasification combined cycle.

	Electricity	Heat	Transport
Renewables	Concentrating Solar Power Solar PV Wind turbine Hydropower Geothermal	Solar thermal Heat pump	
Biomass	Biomass IGCC Biomass CHP	Biomass HP Biomass CHP Biomass gasification Biomass to H_2 Traditional biomass	Biomass to liquid Biomass to H_2
Biomass + CCS	Biomass IGCC + CCS Biomass to liquid + CCS	Biomass to H_2 + CCS	Biomass to H_2 + CCS Biomass to liquid + CCS
Fossil + CCS	Gas CC + CCS Pulverized coal PP + CCS IGCC + CCS Oxfuel PP	Gas to H_2 + CCS Coal to H_2 + CCS	Gas to H_2 + CCS Coal to H_2 + CCS Coal to liquid + CCS
Nuclear	Thermal reactor		
Fuel Switch	Pulverized Coal PP Coal IGCC Gas turbine Gas CC Diesel turbine Coal CHP Gas CHP	Gas HP Gas CHP Gas to H_2 Gas direct Coal HP Coal CHP Coal gasification Coal direct Refinery	Gas to H_2 Coal to H_2 Coal to liquid Refinery

4 Completeness of decomposition

By construction, the secondary energy shares as described in Section 2 fulfill axioms (A2-A4). In the following we proof that algorithm also fulfills axiom (A1), i.e. that the decomposition is complete in the sense that the sum of all technology contributions M_{ij} and the end-use contribution M_j^{eff} is equal to the difference of baseline and policy emissions:

$$M_j = E_j^{\text{bau}} - E_j^{\text{pol}} = \sum_{i:\Delta S_{ij}>0} M_{ij} + M_j^{\text{end}} \tag{6}$$

Inserting equations 4 and 5 into equation 6 and rearranging the resulting terms yields:

$$\begin{aligned}
M_j &= \sum_{i:\Delta S_{ij}>0} M_{ij} + M_j^{\text{end}} && (7)\\
&= \sum_{i:\Delta S_{ij}>0} \Big(\Delta S_{ij}(\bar{\varepsilon}_j - \varepsilon_{ij}^{\text{pol}}) + S_{ij}^{\text{bau}}(\varepsilon_{ij}^{\text{bau}} - \varepsilon_{ij}^{\text{pol}})\Big) - \bar{\varepsilon}_j \sum_i \Delta S_{ij} && (8)\\
&= \bar{\varepsilon}_j \left(\sum_{i:\Delta S_{ij}>0} \Delta S_{ij} - \sum_i \Delta S_{ij} \right) + \sum_{i:\Delta S_{ij}>0} \Big(S_{ij}^{\text{bau}}(\varepsilon_{ij}^{\text{bau}} - \varepsilon_{ij}^{\text{pol}}) - \varepsilon_{ij}^{\text{pol}} \Delta S_{ij} \Big) && (9)\\
&= -\bar{\varepsilon}_j \sum_{i:\Delta S_{ij}\leq 0} \Delta S_{ij} + \sum_{i:\Delta S_{ij}>0} \Big(\varepsilon_{ij}^{\text{pol}} S_{ij}^{\text{bau}} - \varepsilon_{ij}^{\text{pol}} S_{ij}^{\text{pol}} + \varepsilon_{ij}^{\text{bau}} S_{ij}^{\text{bau}} - \varepsilon_{ij}^{\text{pol}} S_{ij}^{\text{bau}} \Big) && (10)\\
&= -\sum_{i:\Delta S_{ij}\leq 0} (E_{ij}^{\text{pol}} - E_{ij}^{\text{bau}}) + \sum_{i:\Delta S_{ij}>0} (E_{ij}^{\text{bau}} - E_{ij}^{\text{pol}}) && (11)\\
&= E_j^{\text{bau}} - E_j^{\text{pol}} && (12)
\end{aligned}$$

As shown, the decomposition of emission reductions into technology and end-use shares is complete for each secondary energy carrier j, and thus also for the total emissions.

5 Sensitivity analysis: Alternative calculation algorithms

As mentioned in Section 3.2 of the main paper, the used algorithm to calculate mitigation shares cannot differentiate between actual end-use reductions and substitutions between secondary energy carriers used for the same final energy type. While this usually does not matter for the results, there are a few instances within ReMIND where this produces counterintuitive results, the most important being the production of hydrogen (H_2) from BioCCS in strong mitigation scenarios.

H_2 is used to supply both heat and transport energy, and in baseline scenarios it is mostly produced from coal, thus having high specific emissions. In policy scenarios, it is mostly produced from BioCCS, resulting in negative emissions. It is therefore used much more strongly than in baseline scenarios and replaces other secondary energy carriers like gas (used for heat) or petrol (used for transport).

In the default algorithm, the increased H_2 is registered twofold - once as "additional emissions due to increased H_2 use", which is counted negatively towards the efficency share[1], and once as "reduced emissions due to a different technology", for which BioCCS receives the full credit for decarbonizing this large share of emission-intensive H_2. In the logic of the model, however, H_2 and gas are quite well substitutable (substitution elasticity of 3 within the final energy type heat), so the hydrogen from BioCCS actually replaces gas or petrol and not emission-intensive coal-H_2.

To test how much we possibly over- or underestimate the contributions from energy efficiency, BioCCS and renewables, we developed two alternative calculation methods:

Alternative method 1: Specific emission intensity from policy run The change of the total amount of a secondary energy carrier is credited either with the specific emission intensity of the policy run or zero, depending on which is larger.[2]

Alternative method 2: Linear substitution within one final energy type Each final energy type (heat, electricity, transport) is treated as if the secondary energies used to supply it can substitute each other linearly. Thus, the average specific abatement credit is calculated for the sum of all secondary energy carriers within one final energy type, not individually for each secondary energy. This average specific abatement credit is then used as $\bar{\varepsilon}_j^{\mathrm{bau}}$ in equations (4) and (5) in Section 2 to calculate both the efficiency and the individual technology contributions.

It should be noted that both alternatives require some rescaling of the specific abatement credit used to calculate the technology mitigation shares, else the sum of individual abatement shares does not add up to the total of mitigated emissions.

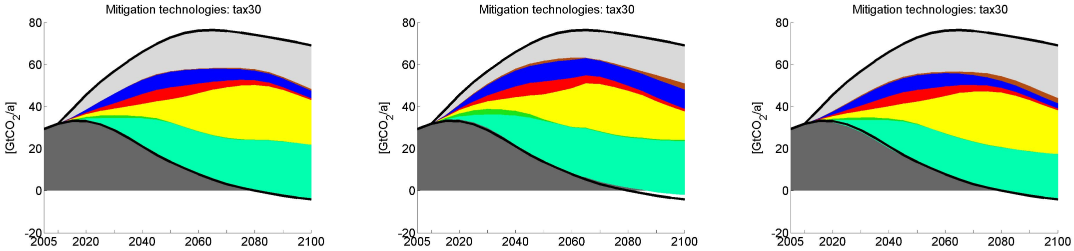
The results of the alternative algorithms are shown in Figure 3. Although the detailed breakdown of mitigation shares over final energy types and time is influenced by the different algorithms, the general trend of the global mitigation shares is quite similar across all three algorithms. When comparing the differences between the different algorithms for secondary energy based mitigation shares with those of primary energy based mitigation shares as described in Section 6, we conclude that the ambiguities can be significantly reduced by using secondary energy based shares.

Alternative method 1: Specific emission intensity from policy run: This method attributes changes of the total level of a secondary energy carrier with the specific emission intensity of a policy run. Thus, reductions of energy use have a much smaller positive mitigation contribution. To still cover the full abatement done in this sector, the mitigation contribution of the remaining technology change has to be scaled up accordingly. This leads to the counterintuitive result that the specific emission reduction achieved through a zero-carbon technology is larger than the specific abatement credit for the displaced emission-intensive technology.

---

[1] To calculate the efficiency share, the total change in secondary energy use is weighted with the specific emissions of the displaced baseline technologies.

[2] Allowing negative specific abatement credits for efficiency would lead to the strongly counterintuitive result that all the credit of the negative BioCCS emissions go to end-use efficiency for *increasing* the use of *negative emission energy*.



(a) Default algorithm (b) Spec. em. factor from policy (c) Linear substitution

Figure 3: Global mitigation shares calculated with different algorithms: (a) default, (b) efficiency is weighted with the specific emission intensity of the policy run, (c) as default, but all secondary energy carriers within one final energy type are treated as one energy carrier.

An example may help to illustrate this problem: In a baseline run, 10 EJ of a secondary energy carrier are used, the specific emission intensity of the supplying technology is 1 GtC/EJ, thus total emissions from this secondary energy carrier are 10 GtC. In the policy run, only 5 EJ of this secondary energy carrier are used, and these 5 EJ are completely decarbonized through a zero-emission technology, thus total emissions are 0 GtC. Using the alternative method 1, the efficiency share would then be zero, as the specific emission intensity of the policy run is zero. Thus, the 10 GtC abatement would be attributed to the 5 EJ of clean energy, resulting in a specific mitigation credit of the zero-carbon technology of 2 GtC/EJ - more than was initially emitted in the baseline.

This effect is strongest in the transport sector, where liquid transport fuels produced from coal are reduced and replaced by liquid fuels from coal with CCS. As the mitigation contribution from demand reduction is weighted less strongly, the fossil+CCS option increases accordingly. Several smaller changes in the two other final energy types where the efficiency share increases at the cost of the renewable contribution lead to an aggregated picture as seen in Figure 3b: the Fossil+CCS mitigation share gains, mostly at the cost of the shares from renewables and energy efficiency.

Alternative method 2: Linear substitution within one final energy type: The advantage of this method is that it partly overcomes the problem of similar secondary energy carriers substituting each other within one final energy type by assuming they substitute linearly and netting out their individual level changes. It thus manages to better differentiate real efficiency gains (reduced total energy use of one final energy type) from substitutions between energy carriers.

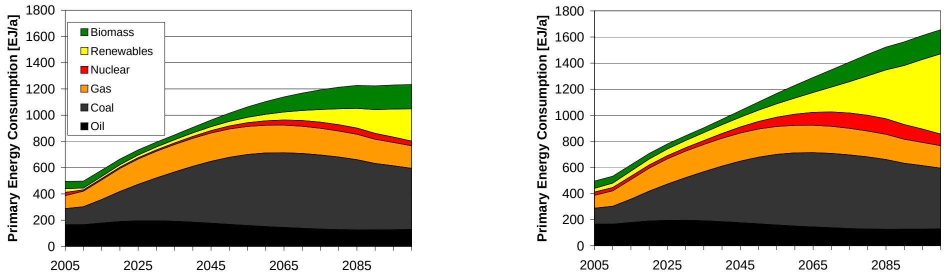
The main drawback is that the algorithm is not exact in representing the substitution within the model as it assumes linear substitution within one end-use type. In contrast, secondary energy carriers substitute non-linearly via a constant elasticity of substitution function in ReMIND. Therefore, the algorithm requires a small ex-post-rescaling of the specific abatement credit for each final energy type.

6 Primary Energy vs. Secondary Energy Accounting

To our knowledge, most existing approaches for the calculation of mitigation shares from integrated assessment scenarios are based on primary energy accounting. As elaborated in Section 3 of the main paper, this is problematic for two reasons: (a) substitutions in the model occur mostly on the secondary level (e.g. one unit of nuclear electricity for one unit of coal-based electricity), rather than on the primary level; and (b) ambiguities in primary energy accounting translate directly into ambiguities in the calculation of mitigation shares.

In order to illustrate the second point, we present PE mixes based on (a) the direct equivalent accounting method, and (b) the substitution method. In direct equivalent accounting, one unit of secondary energy production from non-combustible primary energy (in particular nuclear and non-biomass renewables) is accounted as one unit of primary energy. The substitution method, by contrast, reports primary energy from non-combustible sources as if it had been substituted for combustible energy. See IPCC (2011, Appendix II) for a detailed discussion of primary energy accounting. The different methods result in a factor of three difference in primary energy accounting of fossils and non-biomass renewables. As shown in Figure 4, the difference between PE accounting methods is substantial, in particular for mitigation scenarios with high penetration of non-biomass renewables and nuclear.

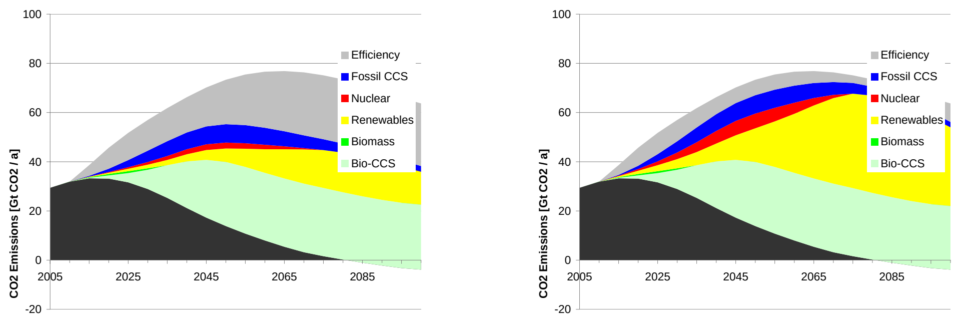
The ambiguity in primary energy accounting translates directly to ambiguity in the calculation of primary energy based mitigation shares: As illustrated in Figure 5, for the substitution method, mitigation shares of nuclear and non-biomass renewables are much larger than in the case of direct equivalent accounting, while efficiency assumes is much higher for direct equivalent accounting compared substitution method. An important advantage of the methodology of secondary energy energy based mitigation shares (Figure 2) is that the ambiguity arising from primary energy accounting is removed.



(a) direct equivalent accounting

(b) substitution method

Figure 4: Primary energy supply for the ReMIND TAX-30 scenario, (a) based on direct equivalent accounting, and (b) based on substitution method.



(a) direct equivalent accounting

(b) substitution method

Figure 5: Illustrative primary energy mitigation shares for the ReMIND TAX-30 scenario based on a simple calculation using an ad-hoc method. The use of (a) direct equivalent accounting, or (b) the substitution method has a strong effect on the resulting mitigation shares.