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Supplementary Materials for

The costs of "costless" climate mitigation

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The PDF file includes:

Methods
Figs. S1 to S3
Tables S1 to S7
References

Methods

Here we provide details of how we derive estimates for the IPCC and McKinsey bottom-up approaches, along with those for the top-down economics IAMs of DICE, FUND, and PAGE. We also report supplementary figures that include the different baseline estimates and wider confidence intervals than those shown in Fig. 1; results from process-based IAMs; and tables of data underlying all figures.

IPCC

We use the data underlying IPCC Figure SPM.7 in the Working Group III Summary for Policy Makers (16). We include all activities that have a quantity associated with a cost. This means that we exclude the mitigation potentials assigned to the following five categories: reduce food loss and food waste; shift to sustainable healthy diets; enhanced use of wood products; electric light duty vehicles; and electric heavy duty vehicles.

At each of the different cost bins (≤0, 0-20, 20-50, 50-100, and 100-200 USD tCO_2-eq^{-1}, reported in \$2020s), we sum the mitigation potential across all categories. This provides an estimate of the mitigation potential in the year 2030 measured in $GtCO_2$-eq per year. Although the IPCC cautions against summing the potentials across activities, it does so in portions of its own analysis. The need for caution about summing potentials is that, in some cases, exercising one option might affect the mitigation potential of another. We nevertheless conjecture that, in most cases, cross-activity effects are likely to be small compared to uncertainty in activity-specific estimates themselves.

We convert this quantity to a percentage reduction using the baseline levels of emissions employed in the IPCC analysis. The median estimate is 60 $GtCO_2$-eq with a range from 54 to 68 $GtCO_2$-eq. We use the median for what we report as the central IPCC estimates in Fig. 1a, and the low and high range that we report for each estimate is based on using the high and low ends of the baseline forecast, respectively. The IPCC describes the baselines as consistent with middle-of-the road scenarios, with typical ones being SSP2 and the Current Policy scenario form the World Energy Outlook 2019. Details are reported in Chapter 12 of the IPCC AR6 WGIII and Table 12.12. We report a wider range of estimates for the highest cost bin. This range is based on the overall uncertainty ranges that the IPCC reports only for the overall potential at the highest cost bin. For this range of estimates, we assume the median baseline to convert the potentials to a percentage reduction in 2030.

The IPCC does report uncertainty ranges in subsequent analysis for the aggregate potentials below \$100. See Working Group III Section 12.2.3 and Table 12.4 (1). The best estimate across all sectors is 38 $GtCO_2$-eq with a range between 32-44 $GtCO_2$-eq. Using the median baseline estimate of 60 $GtCO_2$-eq, this translates into a best estimate of a 63% reduction in 2030 with a range of 53% to 73%. We do not report these separately in our main analysis because the underlying analysis differs, and the range is quite similar to that reported in Fig. 1a at $100, where the best estimate is a reduction of 60% with a range between 53% and 67%.

McKinsey

We use data from the 2009 McKinsey analysis (2) which estimates marginal abatement costs curves for net mitigation in 2030. The baseline scenario assumed in the McKinsey analysis is 70 $GtCO_2$-eq in 2030, with no assumed ranges. This baseline is used to convert the estimate to a percentage reduction in 2030. Because, at least as far as we know, the data underlying the McKinsey analysis are not publicly available, the estimates are approximated from the Global GHG Abatement Cost Curve v2.0. Points on the curve, as shown in Exhibit 1 of the McKinsey analysis, were identified using Graph Grabber 2.0.2. Both corners of each bar representing more than 1 $GtCO_2$-eq of mitigation potential were identified, as well as many finer details. The resulting approximation consists of 157 points. Anomalous jittering in the points were removed by imposing non-decreasing constraints on both the x- and y-coordinates (abatement potential and abatement cost, respectively). This was done by replacing any decreasing sequences with their average value.

Economics focused IAM Estimates

As described in the main text, we solve the models assuming different carbon tax rates per tCO_2-eq. This produces model-based estimates of mitigation potentials in 2030 at different costs that are comparable to the bottom-up estimates. It is worth noting, however, that some of the top-down estimates are inclusive of features that are not considered by the bottom-up accounts. Specifically, the models differ in how they account for technological learning that affects mitigation costs, and the costs include various macroeconomic adjustments that depend on savings and investment decisions.

DICE

We use the Mimi version of DICE 2016R:
https://github.com/AlexandrePavlov/MimiDICE2016.jl

The model is first run with no carbon tax to estimate baseline emissions. The choice variable in DICE is the emissions reduction parameter (MIU), from which the carbon price is inferred. For each desired carbon price, we find the value of MIU that produces this price. Specifically, we impose a MIU level of 0 in 2015, and solve for MIU levels in 2020, 2025, and 2030 such that the average carbon price over these three periods equals the desired price. Baseline emissions for DICE in 2030 are 48.15 Gt, accounting only for CO_2 emissions. DICE does not produce an uncertainty range around its estimates.

FUND

We use the Mimi version of FUND 3.13:
https://github.com/fund-model/MimiFUND.jl/releases/tag/v3.13.0

The model is first run with no GHG taxes to estimate baseline emissions. We then apply each carbon tax level to the model, translating the CO_2 tax to account also for methane and N_2O in CO_2-equivalent terms: methane taxes are 29.8 times greater than CO_2 taxes and N_2O taxes are 273 greater. We evaluate emissions reductions in CO_2-equivalent terms using the same coefficients. Each carbon tax level is simulated with 10,000 Monte Carlo runs across parameter uncertainty. Baseline emissions for FUND in 2030 are 60.5 $GtCO_2$-eq (90% confidence interval of 49 – 72 Gt, accounting for parameter uncertainty).

PAGE

We use the Mimi version of PAGE-2020:
https://github.com/openmodels/MimiPAGE2020.jl/releases/tag/v1.8.5

The model is first run with no GHG taxes to estimate baseline emissions using RCP4.5 and SSP2. Taxes are applied and emissions reductions are evaluated in CO_2-equivalent terms as described for FUND. Each carbon tax level is simulated with 10,000 Monte Carlo runs across parameter uncertainty. Baseline emissions for PAGE in 2030, under the RCP4.5 scenario, are 62.65 $GtCO_2$-eq.

IAM Confidence Intervals for FUND and PAGE

Fig. 1 in the main text reports confidence intervals for FUND and PAGE at the 25-75th percentile of the distribution. For purposes of comparison, Fig. S1 reports the same results with wider confidence intervals, at the 5-95th percentile of the distribution.

Process-Based IAMs

We identify underlying mitigation potentials of six different global energy IAMs included in the ENGAGE data set (13). Different scenarios are based on achieving different end of century carbon budgets (14). We extract from each scenario the resulting emissions for CO_2, methane, and N_2O in 2030, and the carbon price for 2020, 2025, and 2030. The carbon prices we report are the average price in USD $tCO_2\text{-eq}^{-1}$ from all three periods, reported in \$2020s. We report the results for all models that produce these data for multiple carbon budgets, including a policy without additional mitigation: COFFEE 1.1, IMAGE 3.0, MESSAGEix-GLOBIOM 1.1, REMIND-MAgPIE 2.1-4.2, TIAM-ECN 1.1, and WITCH 5.0. The complete set of data for each model are reported in Tables S2-S7, where all values are rounded to the nearest whole number.

Mitigation potential is calculated two ways. First, we compare emissions levels in 2030 under each carbon budget scenario to emissions under each model's scenario without additional mitigation policy. The resulting mitigation levels are near 0% for carbon prices near 0, by construction. That is, these estimates do not account for "costless" mitigation, since any such mitigation is included in the baseline. The corresponding baseline emissions, reported as $GtCO_2$-eq in 2030, for each model is the following: 53.693 for COFFEE 1.1, 62.850 for IMAGE 3.0, 62.037 for MESSAGEix-GLOBIOM 1.1, 62.754 for REMIND-MAgPIE 2.1-4.2, 63.367 for

TIAM-ECN 1.1, and 59.907 for WITCH 5.0. The percentage changes from these baseline are reported in Tables S2-S7 in the "No costless" column.

Second, we use a different approach to derive the percentage reduction inclusive of costless reductions for each model. In this case, we calculate mitigation as the percentage difference between 2030 emissions under each carbon budget scenario and the AIM model's national policies emissions scenario (65.570 $GtCO_2$-eq), which gives the highest emissions across the various models and scenarios. This provides a reasonably consistent baseline, since it follows the socio-economic assumptions used throughout the ENGAGE project, but produces conservative estimates because some negative-cost emissions options are already incorporated into AIM's baseline estimate. As a result, these baseline emissions are lower than the "baseline" scenarios used elsewhere in the IPCC (SSP3-7.0 and SSP5-8.5). Using one of the IPCC baseline scenarios would produce a correspondingly higher estimate of zero-cost mitigation. The percentage reduction for each model relative this baseline are those reported in Tables S2-S7 in the "All" column.

Figs S2 and S3 reproduce Figs 1 and S1 including results from all six global process-based IAMs. The figures illustrate how the process-based IAMs are more closely aligned with the bottom-up estimates then the economics focused IAMs with regard to mitigation potentials and seemingly costless mitigation.

Figures and Tables

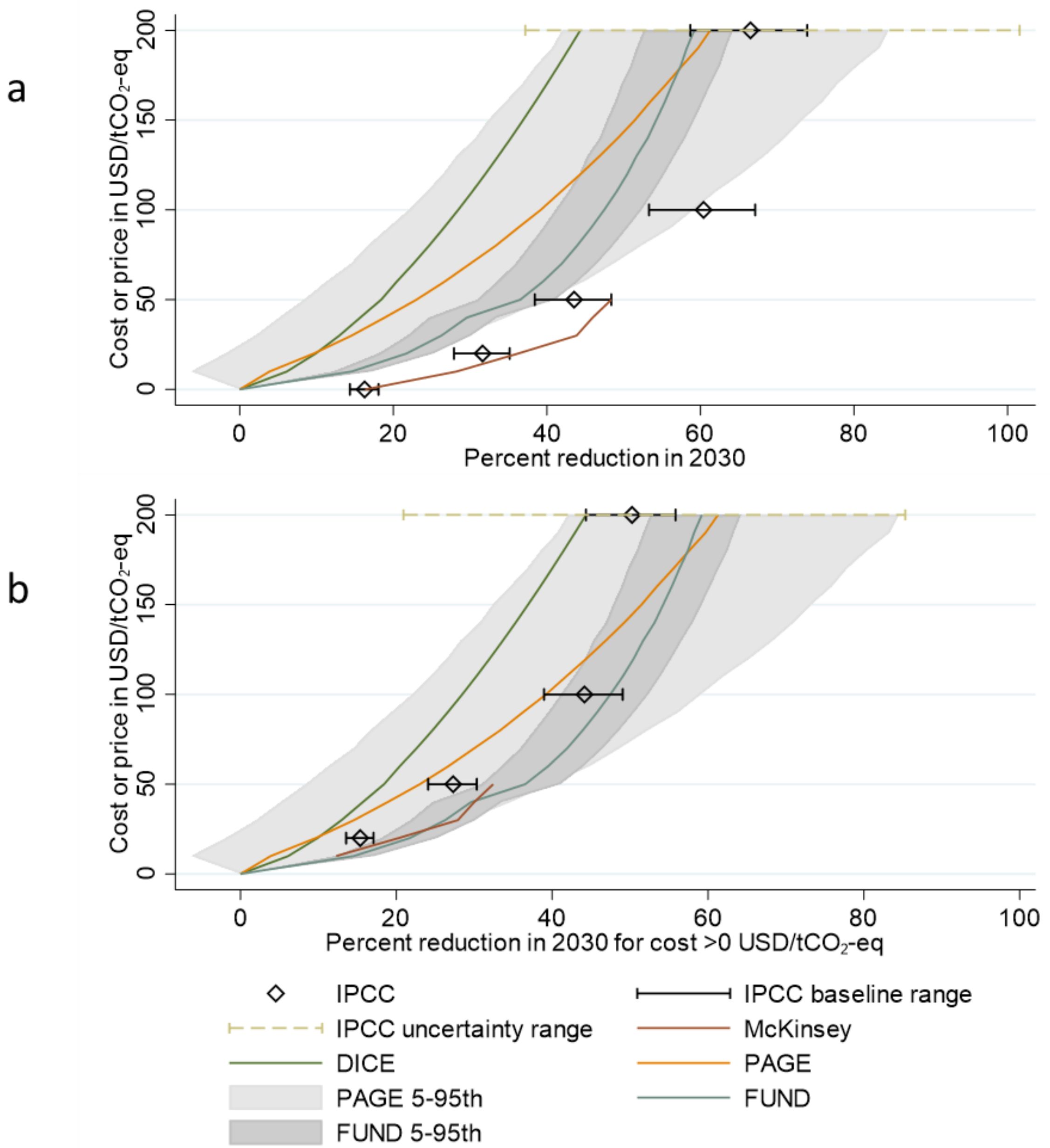

Fig. S1. Comparison of mitigation potentials at different costs. This figure is identical to Fig. 1 in the main text with one exception: the uncertainty range for FUND and PAGE is reported at the 5-95th percent of the distribution rather than at the 25-75th percent level. USD reported in 2020$s.

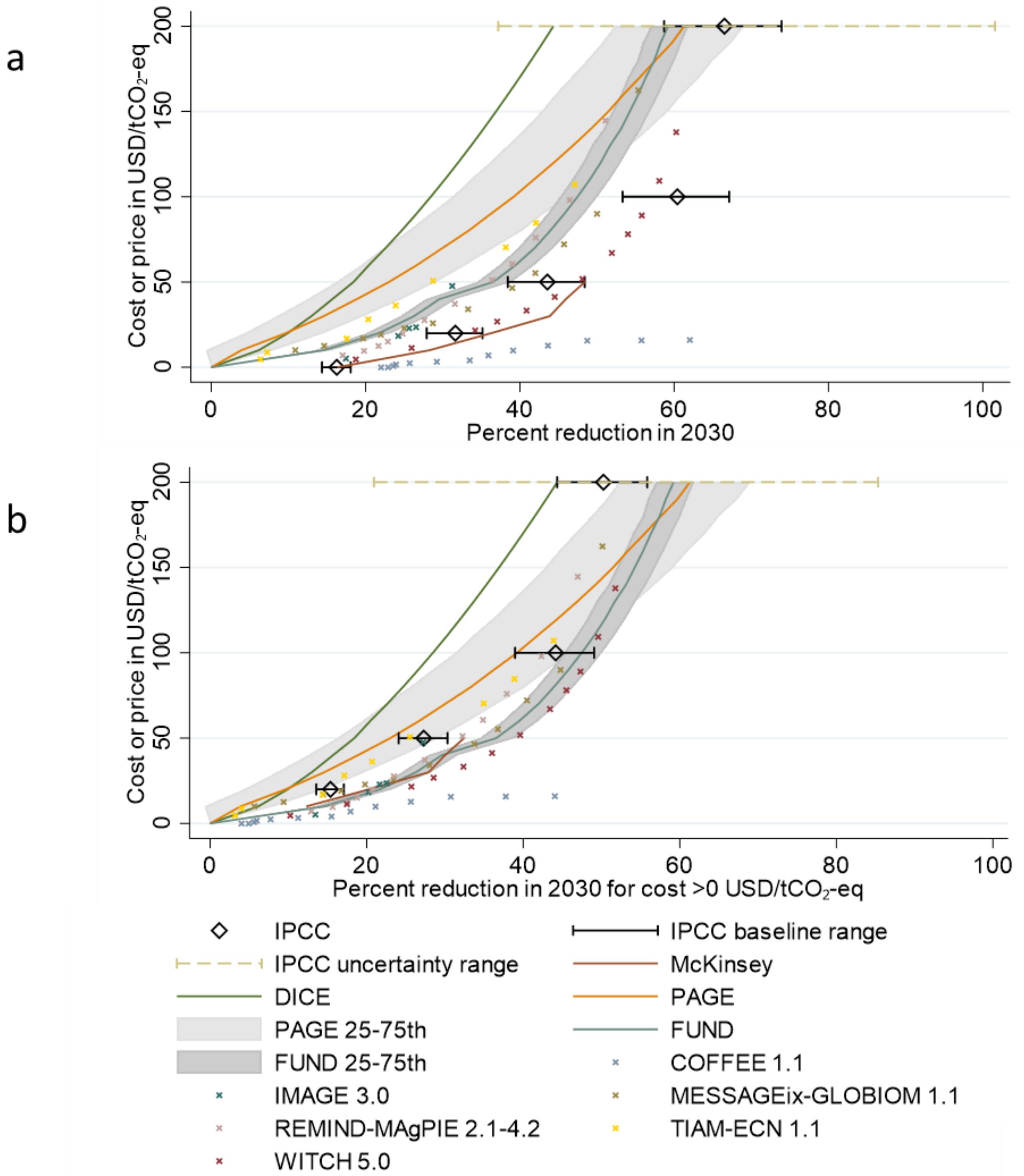

Fig. S2. Comparison of mitigation potentials at different costs including results for the process-based IAMs. This figure is identical to Fig. 1 in the main text with inclusion of results for the six process-based IAMs.

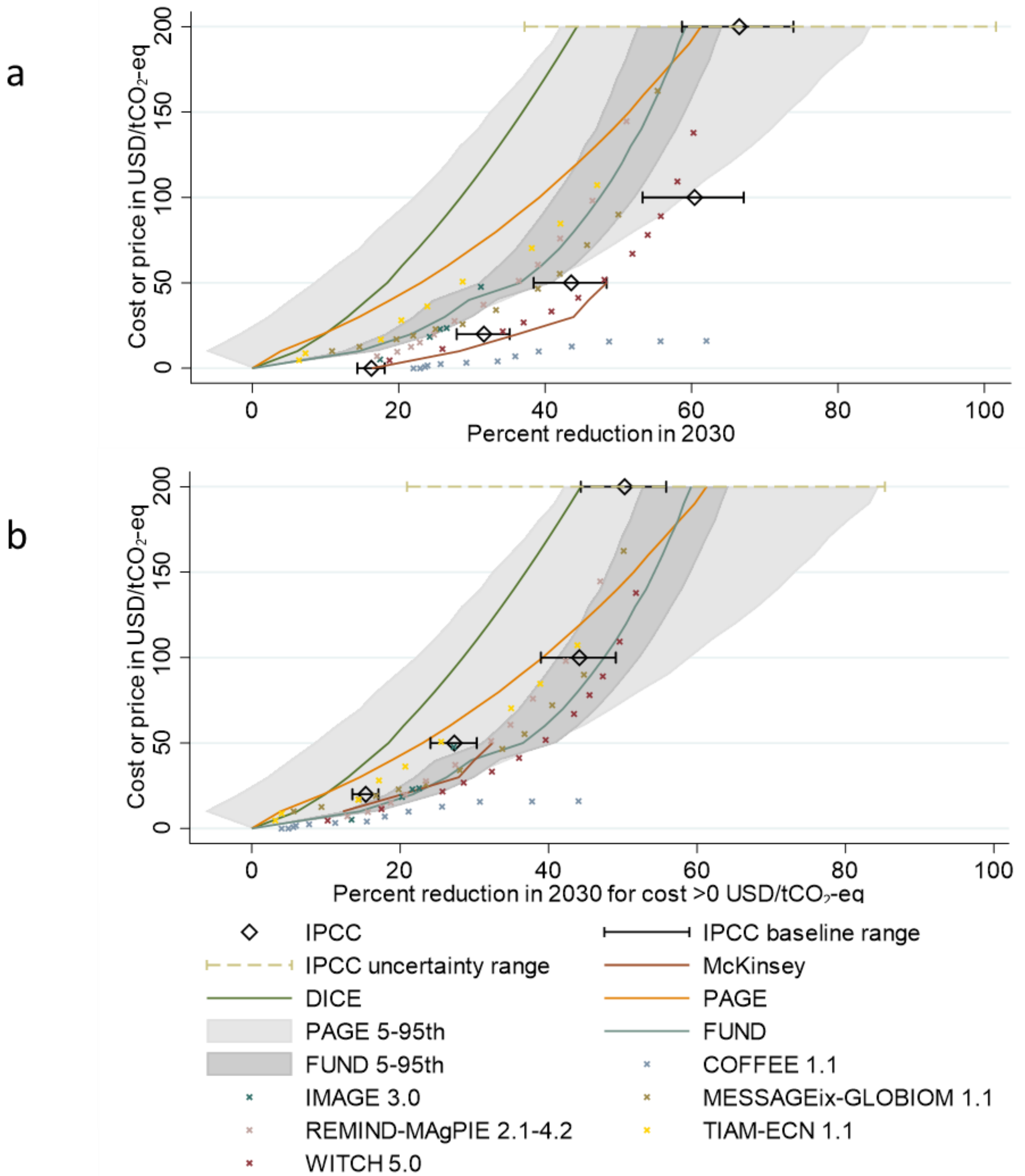

Fig. S3. Comparison of mitigation potentials at different costs, including results for the process-based IAMs. This figure is identical to Fig. S2 except for the wider uncertainty ranges for FUND and PAGE.

Table S1: Mitigation potentials as percentage changes for the models reported in Figs. 1 and S1-S3.

	IPCC			McKinsey	DICE	PAGE					FUND				
Cost		Low	High				5th	25th	75th	95th		5th	25th	75th	95th
0	16	14	18	16	0	0	0	0	0	0	0	0	0	0	0
10				28	6	4	-6	-1	8	15	15	12	13	16	17
20	32	28	35	36	10	10	-2	4	15	23	22	18	20	23	25
30				44	13	15	2	9	20	29	26	22	25	28	30
40				46	16	19	5	13	25	35	30	25	28	32	34
50	44	38	48	48	18	23	8	16	29	40	37	31	34	39	41
60					20	27	11	19	33	45	39	33	37	42	44
70					23	30	14	22	37	49	42	36	40	44	47
80					25	33	17	26	40	52	44	38	42	46	49
90					27	36	19	28	43	56	46	39	44	48	51
100	60	53	67		28	39	22	31	46	59	47	41	45	50	52
110					30	42	24	34	49	62	49	43	47	52	54
120					32	44	26	36	52	65	50	44	48	53	55
130					34	47	28	38	54	68	52	45	49	54	57
140					35	49	31	41	57	71	53	47	51	56	58
150					37	51	32	43	59	73	54	48	52	57	59
160					38	53	35	45	61	76	55	49	53	58	60
170					40	56	37	47	63	78	56	50	54	59	61
180					41	58	39	49	65	80	57	51	55	60	63
190					43	60	41	51	67	83	58	52	56	61	63
200	67	59 [37]	74 [102]		44	61	42	52	69	85	59	53	57	62	64

Table S2: Results for COFFEE 1.1

Modeling scenario	Cost	All	No costless
EN_NPi2020_2500	0	22	4
EN_NPi2020_2000	0	23	5
EN_NPi2020_1800	1	24	6
EN_NPi2020_1600	2	24	6
EN_NPi2020_1400	2	26	8
EN_NPi2020_1200	3	29	11
EN_NPi2020_1000	4	33	16
EN_NPi2020_900	7	36	18
EN_NPi2020_800	10	39	21
EN_NPi2020_700	13	44	26
EN_NPi2020_600	16	49	31
EN_NPi2020_500	16	56	38
EN_NPi2020_400	16	62	44

Table S3: Results for IMAGE 3.0

Modeling scenario	Cost	All	No costless
EN_NPi2020_1400	18	24	20
EN_NPi2020_1000	23	26	22
EN_NPi2020_1200	24	27	23
EN_NPi2020_800	48	31	27

Table S4: Results for MESSAGEix-GLOBIOM 1.1

Modeling scenario	Cost	All	No costless
EN_NPi2020_2500	13	15	9
EN_NPi2020_2000	17	20	14
EN_NPi2020_1800	19	22	17
EN_NPi2020_1600	23	25	20
EN_NPi2020_1400	26	29	23
EN_NPi2020_1200	34	33	28
EN_NPi2020_1000	47	39	34
EN_NPi2020_900	55	42	37
EN_NPi2020_800	72	46	40
EN_NPi2020_700	90	50	45
EN_NPi2020_600	162	55	50

Table S5: Results for REMIND-MAgPIE 2.1-4.2

Modeling scenario	Cost	All	No costless
EN_NPi2020_2500	10	20	16
EN_NPi2020_2000	13	22	18
EN_NPi2020_1800	15	23	19
EN_NPi2020_1600	20	25	21
EN_NPi2020_1400	28	28	23
EN_NPi2020_1200	37	32	27
EN_NPi2020_1000	51	36	32
EN_NPi2020_900	61	39	35
EN_NPi2020_800	76	42	38
EN_NPi2020_700	98	46	42
EN_NPi2020_600	145	51	47

Table S6: Results for TIAM-ECN 1.1

Modeling scenario	Cost	All	No costless
EN_NPi2020_2500	9	7	4
EN_NPi2020_2000	17	18	14
EN_NPi2020_1600	28	20	17
EN_NPi2020_1400	36	24	21
EN_NPi2020_1200	51	29	26
EN_NPi2020_1000	70	38	35
EN_NPi2020_900	85	42	39
EN_NPi2020_800	107	47	44

Table S7: Results for WITCH 5.0

Modeling scenario	Cost	All	No costless
EN_NPi2020_2500	11	26	17
EN_NPi2020_2000	22	34	26
EN_NPi2020_1800	27	37	29
EN_NPi2020_1600	33	41	32

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