AMPERE Work Package 2 (WP2) model comparison study protocol

WP2 Scenario Matrix:

Specific features of the scenarios in WP2 are 1) the consideration of alternative technology futures to better understand the role of major mitigation options in GHG abatement, and 2) the explicit analysis of interim emission targets (for the year 2030) and their consequences for the attainability and costs of meeting long-term GHG concentration levels (450 and 550 ppm CO_2e).

WP2 includes in sum 12 mandatory scenarios that combine above elements as illustrated in the WP2 Scenario Matrix (Table 1). These 12 scenarios are additional to the set of benchmark scenarios common to WP2 and WP3. In addition, for WP2 it is proposed to harmonize energy demand in the baseline scenarios. Modeling teams are encouraged to run a number of "optional" scenarios, if possible (see WP2 scenario matrix).

The scenario matrix has two sections, indicating the technology dimension (variation of technology portfolios and technological change assumptions) as well as the policy dimension (GHG targets) of the scenarios. The technology dimension describes the different combinations of assumptions with respect to energy intensity (energy demand), CCS, nuclear, wind & solar, and bioenergy potentials of the scenarios. For the mandatory scenarios only a variation of energy intensity, CCS, and nuclear needs to be implemented. The variation of other technology assumptions is optional. For further details about assumptions for the technology sensitivity cases see section 4.

The policy dimension defines the combination of short- and long-term targets that should be assumed in the mitigation runs. For each long-term concentration level, two alternative short-term GHG emissions targets (<u>H</u>igh/<u>L</u>ow) are considered (rows in the scenario matrix). Hence, each cell in the matrix corresponds to a scenario that would need to be developed. Note that for some specific combinations of technology assumptions, also a new baseline needs to be developed (e.g. assuming that nuclear is "turned off" would require a new baseline, while assuming the same for CCS typically has negligible or no implications for the baseline).

To limit the number of overall scenarios, it was decided to focus on the 450 ppm CO_2e target for the sensitivity cases exploring the technology dimension (see Table 1). In addition, the implication for 550 ppm CO_2e is explored by two scenarios using the "default technology" assumptions of the models. By doing so, a minimum set of scenarios is derived that explores both the implications of the technology dimension as well the implications of two different long-term targets.

In order to explore the consequences of interim targets for the attainability and costs of long-term targets, it is necessary to distinctly separate short-term emission reductions from their long-term consequences. This is a challenge for perfect foresight models, which will need to run the scenarios myopically, i.e., in different stages. In the first stage, the short-term emission target should be implemented and foresight should be limited to the time-horizon of the short term target. In the second stage, all model variables up to the time-horizon of the short-term target (2030) should be fixed, and the scenario should be run for the remaining time horizon to the end of the century (including the long-term constraint to meet the cumulative CO_2 emissions for the respective 450 and 550 ppm concentration target). This elaborate set-up is necessary in order to avoid model anticipation, which permits the exploration of potential short-term lock-in effects (including the assessment of the potential infeasibility of long-term targets due to relatively higher short-term emission levels).

Table 1: WP2 scenario matrix. The prefix "AMPERE2" is added to all scenario names but is not displayed in this table for the sake of brevity. Mandatory scenarios of WP2 are labeled in red. Additional optional scenarios for WP2 are labeled in black. Scenarios in blue (italics) correspond to the global scenarios that are common across WP2 and WP3. A separate naming is however provided, since these scenarios are harmonized with respect to baseline energy demand (which is not necessary for WP3). For further details on the specification of the technology variations see section 4.

Technology Dimension									
		Default	**Single technologies changed**					**Conventional vs. renewable**	
Energy intensity (energy demand)		Ref	Low	Ref	Ref	Ref	Ref	Ref	Low
CCS		On	On	Off	On	On	On	On	Off
Nuclear energy		On	On	On	Off	On	On	On	Off
Wind & solar		Adv	Adv	Adv	Adv	Cons	Adv	Cons	Adv
Bioenergy potential		High	High	High	High	High	Low	Low	High
Policy Dimension									
Long term scenarios:									
Baseline		*Base-FullTech-OPT*	Base-LowEI-OPT		Base-NucOff-OPT	Base-LimSW-OPT	Base-LimBio-OPT	Base-Conv-OPT	Base-EERE-OPT
450 CO2e		*450-FullTech-OPT*	450-LowEI-OPT	450-NoCCS-OPT	450-NucOff-OPT	450-LimSW-OPT	450-LimBio-OPT	450-Conv-OPT	450-EERE-OPT
550 CO2e		*550-FullTech-OPT*	550-LowEI-OPT	550-NoCCS-OPT	550-NucOff-OPT	550-LimSW-OPT	550-LimBio-OPT	550-Conv-OPT	550-EERE-OPT
Myopic scenarios:									
Short term target	Long term target								
High/2030	450 CO2e	450-FullTech-HST	450-LowEI-HST	450-NoCCS-HST	450-NucOff-HST	450-LimSW-HST	450-LimBio-HST	450-Conv-HST	450-EERE-HST
Low/2030	450 CO2e	450-FullTech-LST	450-LowEI-LST	450-NoCCS-LST	450-NucOff-LST	450-LimSW-LST	450-LimBio-LST	450-Conv-LST	450-EERE-LST
High/2030	550 CO2e	550-FullTech-HST							
Low/2030	550 CO2e	550-FullTech-LST							

The following sections describe specifications of the modeling protocol in more detail, including assumptions with respect to:

1) Baseline scenario and harmonization of energy intensity (demand)
2) Specification of long-term targets
3) Specification of short-term targets
4) Specification of alternative technology set-ups

1. Baseline scenario and harmonization of energy intensity (demand)

The baseline scenario of WP2 builds upon the “no policy baseline” scenario with the harmonized GDP assumptions of AMPERE.

Alternative levels of energy demand represent important sensitivity cases of WP2. Hence, it is proposed to harmonize also energy demand (and thus energy intensity) across the WP2 baselines.

Two different levels of future energy demand are explored: a reference case “Ref”, and a “Low” case (see scenario matrix, Table 1). The aim of the harmonization is to keep the approach as simple as possible, and to derive qualitatively similar baseline demands at a high level of aggregation. Final energy demand should thus be harmonized only on the global level, and each modeling team is free to make own assumptions about the regional development. Also, final energy demand is harmonized only for 2050 and 2100. All teams are flexible with respect to assumptions of the pathway that would lead to those endpoints.

The long-term energy demand in the “Ref” case corresponds to about a continuation of historical energy intensity improvement rates. As a guide for deriving associated level of global final energy demand by 2100, we rely on estimates of the GEA (Global Energy Assessment) for the historical rates of EI improvements, and apply these to the AMPERE GDP projections for the future.

The (“Low”) energy intensity level represents an ambitious efficiency pathway for the world, corresponding roughly to a 50% increase of the energy intensity improvement rate compared to the “Ref” case.

The resulting ranges for the final energy demand of “Ref” and “Low” energy intensity cases are shown in Table 2. Harmonization of final energy should be done for total final energy excluding non-commercial biomass.

In order to improve comparability of assumptions for the harmonization for final energy, Table 3 provides adjustment factor for different final energy definitions. For example, models that do not include the use of fuels for non-energy carriers (e.g. oil used for polyethylene production, natural gas for fertilizer production) should adjust the harmonization ranges from Table 2 by 10% downwards.

Table 2: Global final energy demand by 2050 and 2100 that should be used for the harmonization of baselines under "Ref" and "Low" energy intensity assumptions (scenarios AMPERE2-Base-FullTech-OPT and AMPERE2-Base-LowEI-OPT). The harmonization range corresponds to ±5% of the central final energy demand estimate. Note that harmonization of energy demand should be done only for AMPERE2-Base-FullTech-OPT and AMPERE2-Base-LowEI-OPT (ie, other baselines that explore alternative technology set-ups should be derived from AMPERE2-Base-FullTech-OPT and AMPERE2-Base-LowEI-OPT and should thus show energy demand responses resulting from the technology variations).

	"Ref" energy intensity case	"Low" energy intensity case
Rate of EI improvement (%/yr), 2010-2100	~ 1.3%/yr	~ 1.9%/yr
Harmonization range for total final energy demand (excluding non-commercial biomass)	2050: 655-725 EJ 2100: 910-1000 EJ	2050: 490-540 EJ 2100: 520-570 EJ

Table 3: The following correction factors should be used in case some energy uses are not considered in total final energy or in case some supply-side energy uses are reported at the level of final energy

	Correction factor in % (to be applied to final energy ranges in Table 2)
If the following energy uses are included in the total final energy reported by your model, please apply the following correction factor:	
Energy use of resource extraction (e.g., coal, oil, natural gas)	+6%
Transmission and distribution losses (e.g., electricity, natural gas, natural gas pipelines)	+2%
Losses of central heat generation	+1%
Losses of oil refineries	+5%
If the following energy uses are NOT included in the total final energy reported by your model, please apply the following correction factor:	
fuels for non-energy carriers (e.g. oil used for polyethylene production, natural gas for fertilizer production)	-10%

Notes:

1) Factors are based on IEA energy balances.
2) Factors should be applied to both 2050 and 2100 ranges

Factors are additive. For instance if a model does include losses from central heating as well as losses from refineries in its final energy reporting, the harmonization rage in Table 2 should be corrected upwards by 6% (= 1% for losses of heat, and 5% for the losses in refineries)

2. Specification of long-term targets

WP2 considers two long-term climate targets corresponding to the stabilization of CO_2e concentrations at 450 and 550 ppm by the end of the century.

For the implementation of these targets into the models, a long-term cumulative CO_2 emissions budget (2000-2100) shall be implemented. In order to enhance comparability between the scenarios in WP2 and WP3, both work packages use the same cumulative emissions budgets. Models which consider also non-CO_2 GHGs (N_2O, CH_4, SF6, CF4, and long-lived halocarbons) should use the resulting CO_2-price from the cumulative CO_2 budget constraint to price non-CO_2 gases.

Table 4 includes the cumulative CO_2 emissions budgets over the course of the century (2000-2100) that should be used as a constraint for the 450 and 550 CO_2e ppm targets. Some fraction of this emission budget will be spent in the first stage in order to meet the pre-specified emission targets in 2030. The scenarios should allocate remaining cumulative emissions (2030-2100) so that they stay within the cumulative emission budget of the full century (for further details see specification of short-term targets).

Table 4: Cumulative CO_2 emission budgets

Long-term target	Cumulative CO_2 emissions
450 ppm CO_2e	*Models with time horizon to 2100:* 2000-2100: 1500 $GtCO_2$ (including all sectors and land-use) (Models that do not include CO_2 emissions from land use, should use fossil fuel and industry emissions budgets of 1400 $GtCO_2$ for the time horizon of 2000 and 2100)
	Models with time horizon to 2050: 2000-2050: 1500 $GtCO_2$ (including all sectors and land-use) (Models that do not include CO_2 emissions from land use, should use fossil fuel and industry emissions budgets of 1400 $GtCO_2$ for the time horizon of 2000 and 2050)
550 ppm CO_2e	*Models with time horizon to 2100:* 2000-2100: 2400 $GtCO_2$ (including all sectors and land-use) (Models that do not include CO_2 emissions from land use, should use fossil fuel and industry emissions budgets of 2400 $GtCO_2$) *Models with time horizon to 2050:* 2000-2050: 1800 $GtCO_2$ (including all sectors and land-use) (Models that do not include CO_2 emissions from land use, should use fossil fuel and industry emissions budgets of 1700 $GtCO_2$ for the time horizon of 2000 and 2050)

3. Specification of short-term targets

Short-term targets are defined in terms of emission levels by 2030 as given in Table 5, Table 6, and Table 7.

Each team is flexible to choose its own heuristics for defining the emission pathway to 2030. The short-term pathway should depict a smooth transition from the base year to 2030 (without discontinuity).

For teams who require an emission pathway to 2030, the emission trajectory between 2000 and 2030 is also provided in Table 7-9 below (the pathway is only provided as information for the teams that need a pathway to reach the 2030 target).

<u>Coverage of emission sources:</u>

Not all models in AMPERE have a full coverage of all sectors and GHG emissions. Short-term targets are thus defined for different groups of models, according to the emission sources/categories that each model can cover:

- Models that include all GHGs (CO_2 from fossil/industry, CO_2 from land-use, N_2O, CH_4, SF6, CF4, and long-lived halocarbons), should use total GHG emissions in CO_2e for the target for 2030.
- Models that cover total CO_2 (including land-use), should use total CO_2 emissions for the target by 2030.
- Models that cover CO_2 from fossil/industry only, should use fossil/industry CO_2 emissions for the target by 2030.

Note: Models should always aim to cover as many GHGs in the short-term target as possible. CO_2e models should thus not use CO_2-only targets. This is important in order to stay comparable to the ongoing policy debate for short-term emissions targets and pledges, which is predominantly in CO_2e.

<u>Implications for the transition from short-term to the long-term target:</u>

As indicated further above, the scenarios of WP2 should be run myopically (with limited foresight). In the first stage the scenarios are constraint by the emissions target for 2030. In the second stage (2030-2100) a cumulative emissions constraint should be applied.

In order to stay consistent between the work packages, WP2 and WP3 share the same cumulative emission budget for the long-term target, which is defined in terms of total CO_2 emissions. This implies that models with full representation of all GHGs would need to apply a short-term target in CO_2e, and then switch to the regime of the second stage with a cumulative budget for total CO_2 (for the long-term target). Similar to WP2, the resulting CO_2 price from the cumulative CO_2 budget constraint should be used to price non-CO_2 gases in the second stage (2030-2100). (CO_2-only models should obviously apply CO_2 emissions targets for the short as well as long term).

<u>Stringency of the short-term target:</u>

The ”High” short-term target corresponds to modest efforts in reducing GHG emissions, and is roughly consistent with a lenient interpretation of the national Copenhagen pledges and their extrapolation to 2030.

The "Low" short-term target corresponds to a relatively higher effort in reducing GHG emissions, and is consistent with a stringent interpretation of the national Copenhagen pledges (and their extrapolation to 2030).

Both high and low short-term emission targets are significantly above the "optimal" 2030 CO_2 emission level for reaching 450 ppm CO_2e in the long term. The assessment will thus help to understand whether the "gap" in emissions by 2030 will be prohibitive for meeting the long-term target, or whether the "gap" can be closed by increasing stringency of emission controls post 2030.

Estimates of the emission pathway to 2020 are based on an analysis of national pledges by Michel den Elzen. Extrapolation of the pledges to 2030 is based on the observed stringency of emission reductions by 2020.

Table 5, Table 6, and Table 7 summarize the characteristics of the short-term emission pathways for the high and low 2030 emissions targets in terms of total GHGs (CO_2e), total CO_2, and fossil/industry CO_2.

Each modeling team should implement the emission target for 2030 with a maximum allowed deviation of ±0.5 $GtCO_2$. In addition, the short-term emissions for 2000, 2010 and 2020 are provided as a guide for those models that require an emission pathway for the implementation.

Also shown in the Table 5, Table 6, and Table 7 is the long-term cumulative emission budget between 2030 and 2100, depending on whether the "high" or "low" short-term target was implemented. For models covering all Kyoto GHGs, the allowable cumulative emissions between 2030 and 2100 will differ across models, and depend on the model-specific trade-off of CO_2 and non-CO_2 gases. See footnote 2 of Table 7 for further explanations.

Table 5: Definition of short-term targets to 2030 for models that cover fossil and industrial CO_2 only. The cumulative emission budget for 2030 to 2100 depends on the fraction of allowable cumulative emissions for the full century that has been spent by 2030. These residual cumulative emissions (2030-2100) are provided in separate columns on the right-hand of the table. They should be used as cumulative emission constraints for the second stage of the scenarios. All values in $GtCO_2$ (considering only fossil fuel and industrial emissions).

	Short-term emissions pathway to 2030				Cumulative CO_2 emissions (short-term) 2000-2030	Cumulative CO_2 emissions 2030-2100 (450 ppm)	Cumulative CO_2 emissions 2030-2100 (550 ppm)
	2000	2010	2020	**2030 (target)**			
High short-term target ("H")	24.7	32.1	38.4	**44.2**	1049	351	1351
Low short-term target ("L")	24.7	32.1	35.9	**37.3**	990	410	1410

Table 6: Definition of short-term targets to 2030 for models that cover total CO_2 only. The cumulative emission budget for 2030 to 2100 depends on the fraction of allowable cumulative emissions for the full century that has been spent by 2030. These residual cumulative emissions (2030-2100) are provided in separate columns on the right-hand of the table. They should be used as cumulative emission constraints for the second stage of the scenarios. All values for total $GtCO_2$ (including land-use emissions).

	Short-term emissions pathway to 2030				Cumulative CO_2 emissions (short-term) 2000-2030	Cumulative CO_2 emissions 2030-2100 (450 ppm)	Cumulative CO_2 emissions 2030-2100 (550 ppm)
	2000	2010	2020	**2030 (target)**			
High short-term target ("H")	28.9	36.0	41.3	**46.6**	1151	349	1249
Low short-term target ("L")	28.9	36.0	38.3	**39.3**	1084	416	1316

Table 7: Definition of short-term targets to 2030 for models that cover all Kyoto GHGs ($GtCO_2e$). Note that the emission budget for 2030-2100 is defined in "total CO2", and will thus differ across models (depending on the corresponding short-term emission trends of total CO_2 emissions). The 2030-2100 budgets can thus not be provided in the table.

	Short-term emissions pathway to 2030[1]				Cumulative CO_2e emissions (short-term) 2000-2030[1]	Cumulative CO_2 emissions 2030-2100 (450 ppm)[2]	Cumulative CO_2 emissions 2030-2100 (550 ppm)[2]
	2000	2010	2020	**2030 (target)**			
High short-term target ("H")	39.4	48.2	54.6	**60.8**	1529	NA.	NA.
Low short-term target ("L")	39.4	48.2	51.0	**52.8**	1452	NA.	NA.

[1] All values in $GtCO_2e$ (including all Kyoto GHGs)

[2] The long-term budget of all AMPERE scenarios is defined in terms of CO_2-only emissions (including fossil fuels and land-use emissions), while the short-term emission target for 2030 in WP2 is defined in CO_2e (including all Kyoto gases). This implies that the residual budget for 2030-2100 emissions will differ across models, and depend on the model-specific trade-off of CO_2 and non-CO_2 gases. In order to derive cumulative 2030-2100 emission budgets for the second stage of the scenarios (2030-2100) apply the following formula for 450ppm: *1500 $GtCO_2$ – emissions of total CO_2 vented over the period of 2000-2030*. For the 550ppm target please use the following formula: *2400 $GtCO_2$ – emissions of total CO_2 vented over the period of 2000-2030*.

Infeasibility of scenarios

Some combinations of short-term and long-term targets may be found infeasible to reach in some of the modeling frameworks. This is important information and the infeasibility of any of the scenarios should be reported.

4. Specification of alternative technology set-ups

The specification of alternative technology set-ups builds upon the modeling protocol of the EMF27 modeling comparison. The aim is to stay consistent with EMF27 to generate synergies, but also to maximize comparability across the projects. For the specification of energy demand and energy intensity assumptions see also Section 1.

4.1 Carbon capture and Storage (CCS):

on: *CCS fully available* in the climate mitigation runs.

off: *No CCS allowed in all energy sectors, in all regions, and for all combinations with fossil fuel, bioenergy and industrial uses* (with the exception of those marginal uses already foreseen in the baseline e.g. for EOR).

4.2 Nuclear energy:

on: *Nuclear energy fully available* (to the extent foreseen by individual models)

off: *Phase-out of nuclear energy after 2010.* Phase-out is defined as no construction of new nuclear power plants beyond those already under construction (excluding planned and proposed plants). In addition, no lifetime extensions beyond the retirement rate assumed in the models should be implemented. This reflects the concept of the “off” case being triggered by public skepticism about nuclear technology. For information on new nuclear power plants under construction or planned see www.world-nuclear.org/info/reactors.html. The website also contains up-to-date information on operating plants which takes into account the permanent shutdown of several nuclear units in 2011.

4.3. Solar and wind energy:

Variations between “conservative technology” and “advanced technology” assumptions shall be implemented in terms of imposing an upper limit to the share of solar and wind electricity supply in the electricity sector. This constraint may serve as an aggregate measure for technology limitations e.g. due to grid integration requirements, as well as institutional and other barriers.

Conservative: The share of electricity production from solar and wind technologies together is limited to 20% of total electricity supply. All solar and wind electricity generation technologies should count towards this constraint, including all wind turbines (with and without onsite storage and/or backup), solar PV (with and without onsite storage and/or backup), and Concentrating Solar Power (with and without thermal storage). The constraint is supposed to reflect not only the technical challenges associated with the integration of intermittent electricity generation, but also economic and institutional barriers that may also limit the diffusion of these technologies.

Hypothetical backstop technologies (which could be interpreted as solar and wind technologies) that are assumed to be fully dispatchable should not be limited by the share constraint. If models include such backstop technologies, modeling teams should note this in the comment tab of the reporting template (including LCOE or capital cost information for the backstop) and report the electricity output in the “Secondary Energy|Electricity|Other” field. The techno-economic assumptions for solar and wind electricity technologies should be adjusted to reflect a more conservative estimate of the techno-economic performance of these technologies. Recommended investment cost increases compared to the advanced case are specified in the table below (see also Appendix A.1 for a specific example). These recommendations are aimed at improving comparability of the conservative wind and solar scenario across models.

Table 8: Recommended investment cost increases (compared to the advanced case) for solar and wind electricity generation

	2050	**2100**
Solar PV	40-80%	60-100%
Concentrating Solar Power (CSP)	10-30%	20-40%
Wind	10-25%	25%-50%

Advanced: *Advanced techno-economic assumptions for solar and wind technologies for electric and non-electric generation.* It is left to the modeler's choice what is being considered "advanced" with respect to the model default assumptions. If models usually assume an expansion constraint on the share of solar and wind technologies in the electricity sector, they should make sure to choose this constraint less stringent than in the conservative case.

4.4. Bioenergy:

For bioenergy, variations shall concern low and high assumptions about the sustainable global bio-energy resource potential.

Low: *Total global bio-energy supply for all sectors from purpose grown bio-energy crops (1st and 2nd generation), residues and municipal solid waste shall be limited to 100 Exajoule per year throughout the 21st century.* The 100 EJ correspond to primary energy and should not include non-commercial biomass.

High: Total global bio-energy supply shall top out at the level generated endogenously by the model (under favorable assumptions about sustainable bio-energy use).

Appendices:

Appendix A.1: Example of assumptions for reference and advanced states of renewable energy technologies

Source: Clarke, L., P. Kyle, M. Wise, K. Calvin, J. Edmonds S. Kim, M. Placet, S. Smith (2008) CO2 Emissions Mitigation and Technological Advance: An Updated Analysis of Advanced Technology Scenarios. PNNL Report 18075.

Solar and wind technology cost assumptions for reference and advanced scenarios

			Reference				Advanced		
		2005	2020	2050	2095		2020	2050	2095
Central PV									
Capital cost	$/kW	6875	4525	2468	1758		3446	1381	947
O&M cost	$/kW-yr	25	25	18	15		22	16	12
Storage cost adder	$/kW	480	413	342	306		355	225	180
Rooftop PV									
Capital cost	$/kW	9500	6278	3583	2793		4258	2246	1654
O&M cost	$/kW-yr	100	50	30	20		30	20	15
CSP									
Capital cost	$/kW	3004	2786	2397	1913		2219	1770	1413
O&M cost	$/kW-yr	47	43	37	30		34	27	22
CSP with storage									
Capital cost	$/kW	6008	5573	4795	3827		3731	2976	2375
O&M cost	$/kW-yr	47	43	37	30		34	27	22
Wind									
Capital cost	$/kW	1167	1124	1043	932		1082	931	743
O&M cost	$/kW-yr	36	30	28	26		30	27	22
Storage cost adder	$/kW	658	566	469	419		486	309	246