POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

Integrated assessment of enhanced weathering

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Outline

1. **Introduction**

2. **Preliminary considerations**
    - **Grain size**
    - **Limitations**

3. **Implementation**

4. **Model results**
    - **Standard implementation**
    - **Sensitivity analysis: grain size**
    - **Technological limitations: limited bioenergy, no CCS**

5. **Summary and Discussion**

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Introduction

Weathering of silicate rock consumes atmospheric CO_2

Fresh silicate rock + CO_2 ⇩ + H_2O
⇨ clay + HCO_3^- + cations

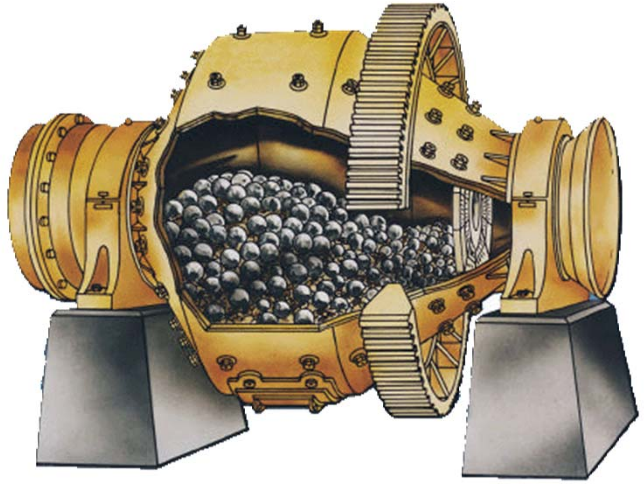
Slow process!
→ Efficient on geological time scales to balance the atmospheric CO_2 content

How can we enhance the natural process?
- fast weathering minerals
- small grain sizes (powder, flour)
- warm and moist regions

Introduction

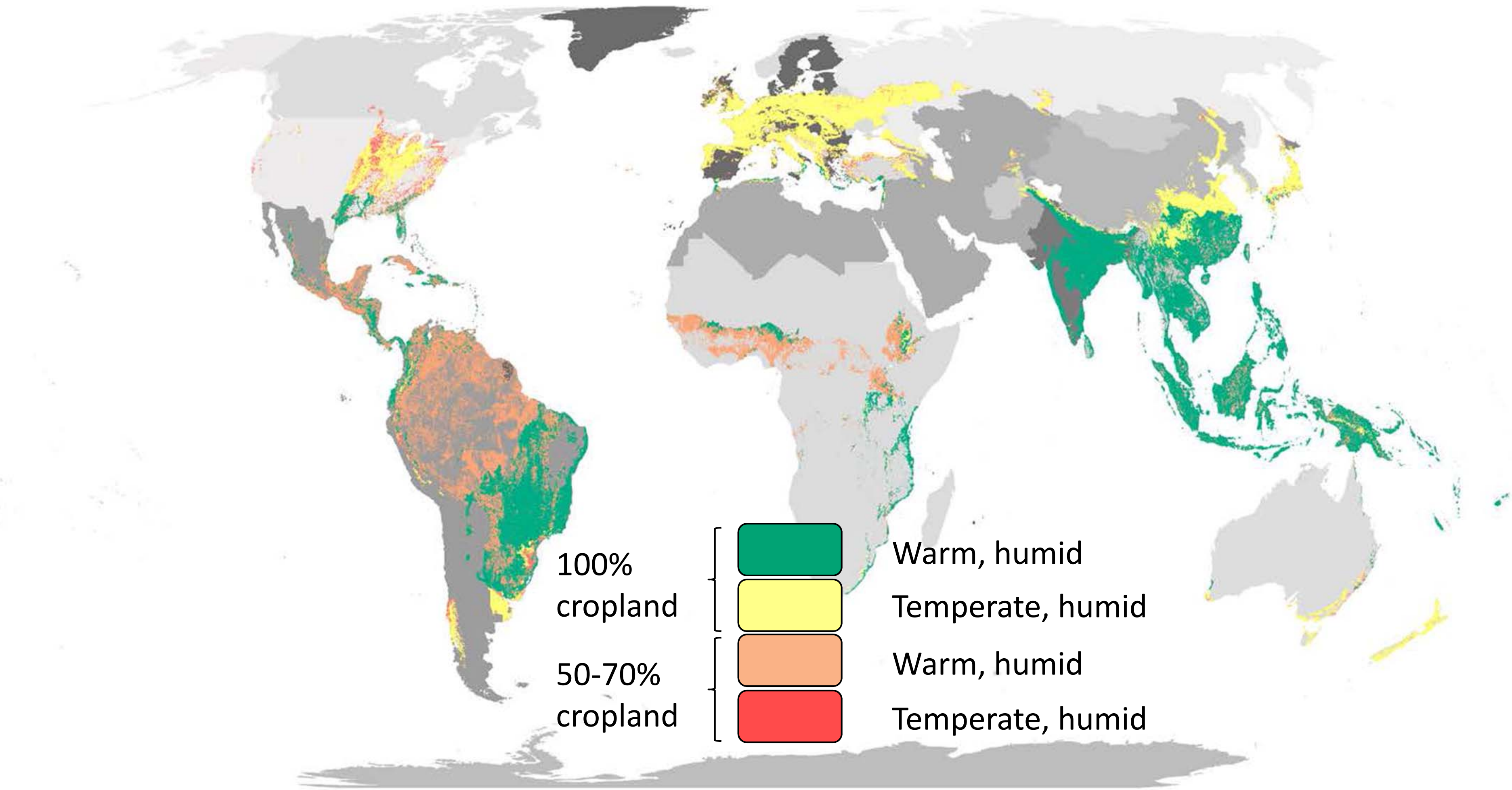
Mining of minerals

Grinding



Spreading on crop fields

Suitable application areas



Why enhanced weathering?

IPCC AR5: negative emissions important for 2° target

4 options:

1. **Bioenergy + CCS (BECCS)**
2. **Afforestation**
3. **Direct air capture (DAC)**
4. **Enhanced weathering of rocks (EW)**

Problems of other options:

- **Pressure on land (BECCS, afforestation)**
- **CCS not yet available (BECCS, DAC)**

Side effects

Negative side effects:

- **Environmental costs of mining**
- **Potential mobilization of trace metals**

Positive side effects:

- **Increase of coastal zone water pH**
- **Supply of nutrients**

Basalt suitable for EW, application planned in India to fertilize soil

Costs and Revenues

Costs

- **Mining, spreading: mass dependent (45-75 \$/ t CO_2)**
- **Grinding:**
  - Energy demand $\mathrm{E} \sim x^{-0.87}$ (x: grain size)
  - disproportional increase of capital costs for small grain size
  - capital + O&M costs: 6 \$/ t CO_2
  - electricity costs ~ 20 \$/ t CO_2 (dependent on grain size, electricity price)

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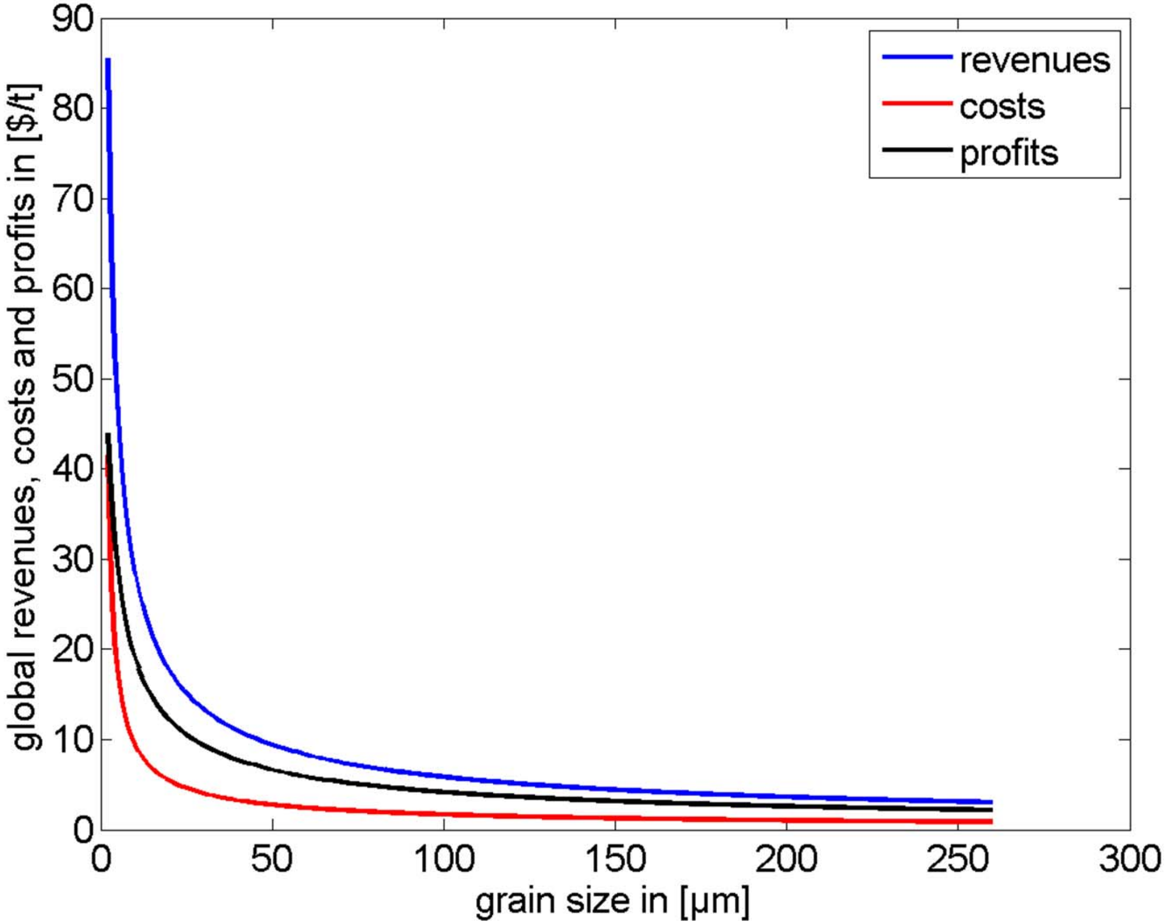
Revenues

- Amount of carbon removed x CO_2 price
- Weathering rate [%/yr] $\delta \sim x^{-0.5}$ (x: grain size)
- Assumption: There is an upper limit to the mass per area
- Weathering rate determines maximum potential of negative emissions

Is there an „optimal“ grain size?



→ **no, the smaller the better**

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Limitations to grain size

- Validity of functions
  - Grain size vs. weathering rate, energy input
    valid down to about 2 µm (weathering rate ≈ 50%)

- Technical limitations
  - 10 µm close to current technical feasibility (weathering rate ≈ 9%)
  - Capital costs may increase disproportionally for grain sizes lower than 10-20 µm

- Particulate matter pollution?
- Water limitation? Amount of CO_2 transported to material?

→ Explore with sensitivity analysis

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Implementation

- REMIND: energy-economy model, perfect foresight, intertemporal optimization
- 11 world regions
- In each region: four grades
  - Warm or temperate climate
  - Continuous or fragmented crop fields
- Build up capacities for grinding; determine amount of ground stone available for spreading in each time step
- Model will start using EW when carbon price is high enough to cover costs

Enhanced weathering as a mitigation option

- **When and to which extent deployed?**
- **Interaction with energy system?**
  - **Energy demand**
  - **Negative CO_2 emissions**
- **Interaction with other mitigation options?**
  - **Especially other carbon dioxide removal technologies as bioenergy + CCS, afforestation, direct air capture complements or substitutes?**

Outline

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- Preliminary considerations
    - Optimal grain size
    - Limitations
- Implementation
- **Model results**
    - **Standard implementation**
    - **Sensitivity analysis: grain size**
    - **Technological limitations: limited bioenergy, no CCS**
- Summary and Discussion

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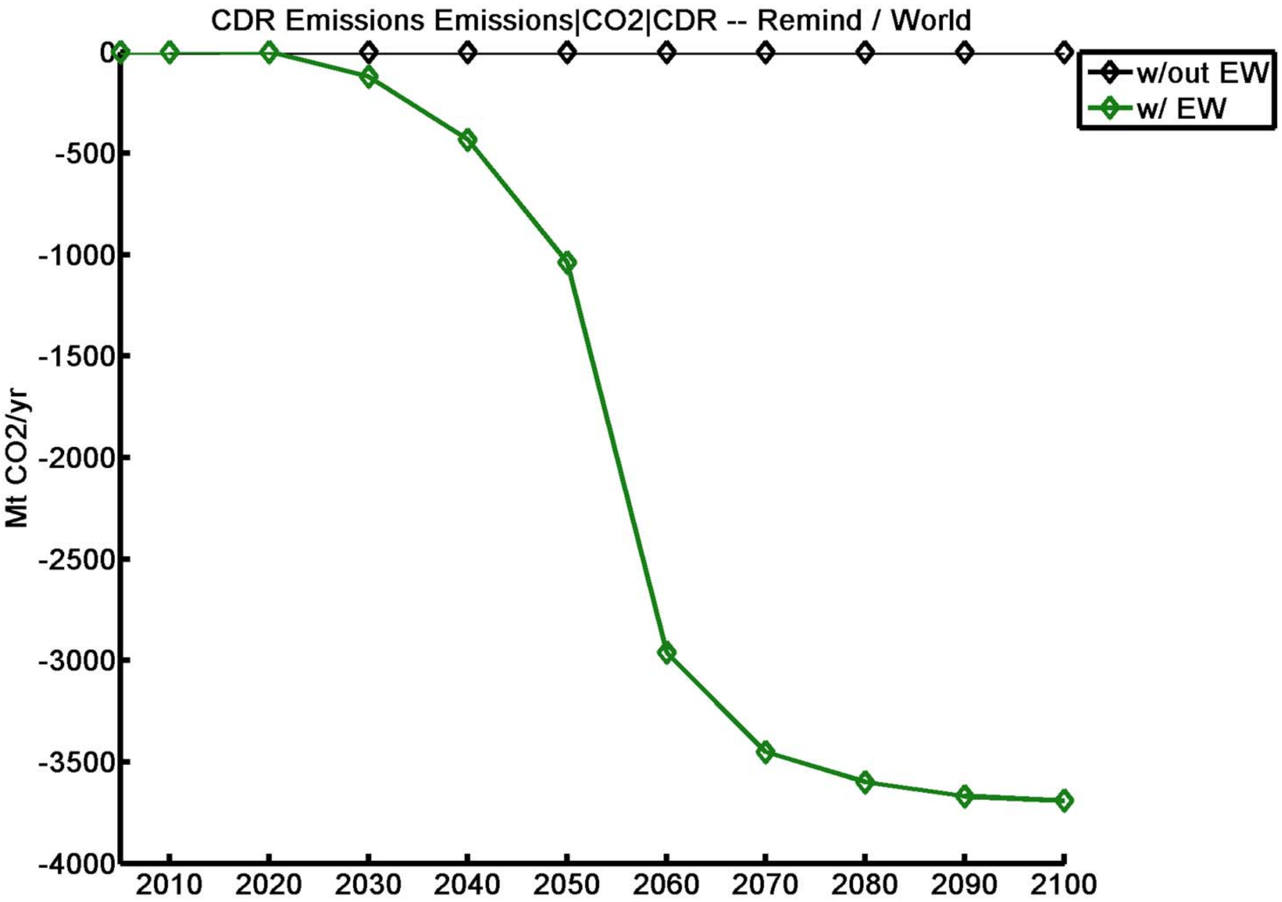
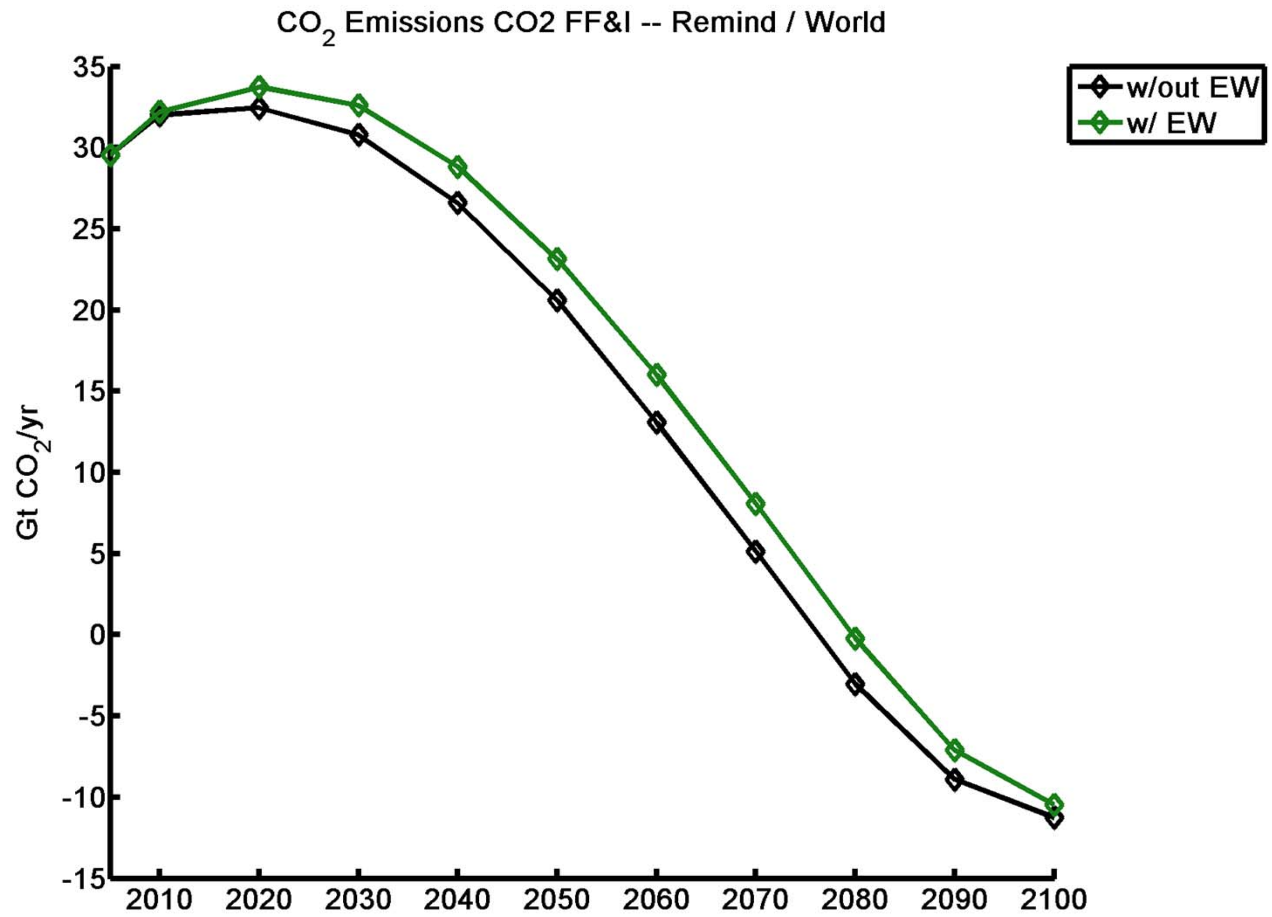
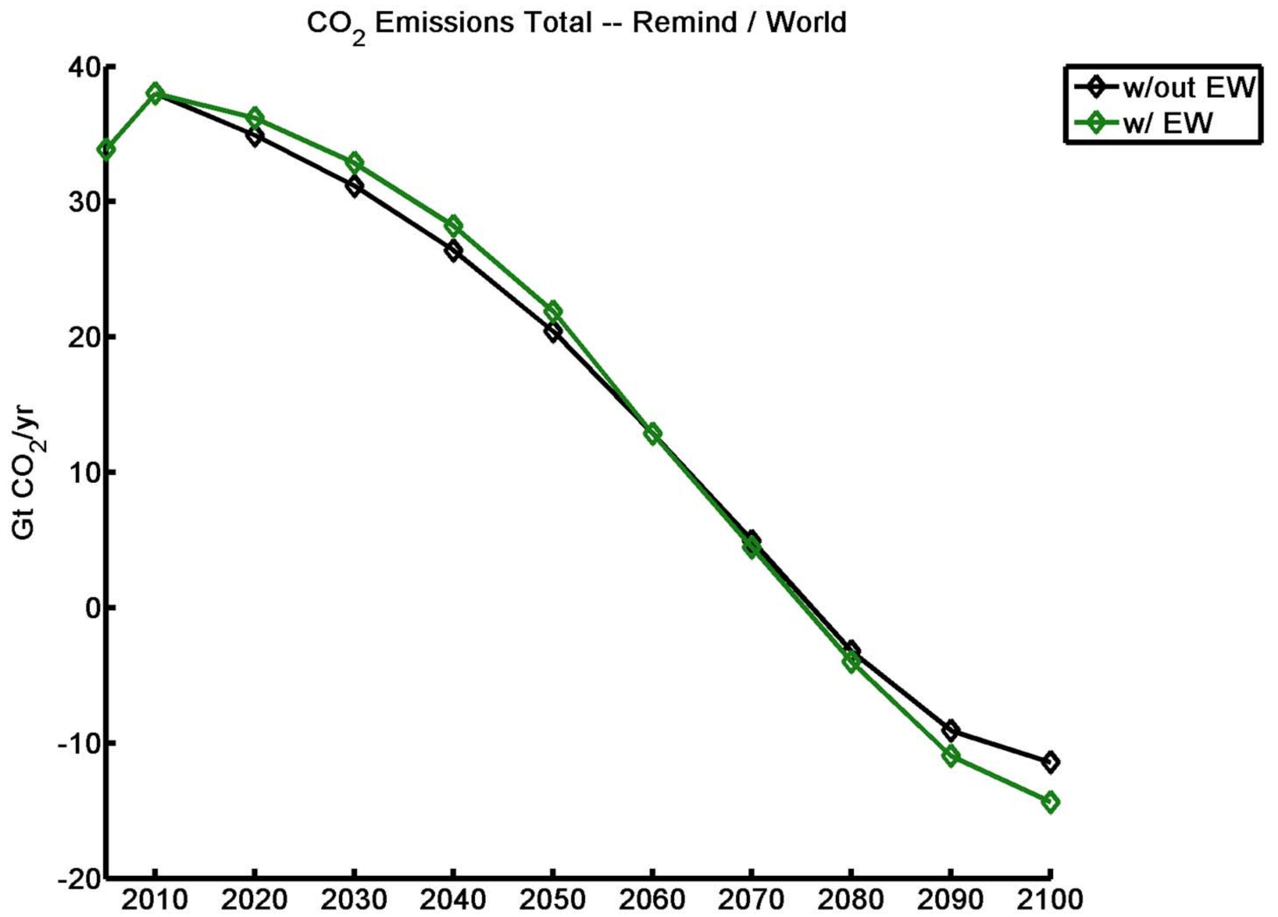
Negative Emissions from EW



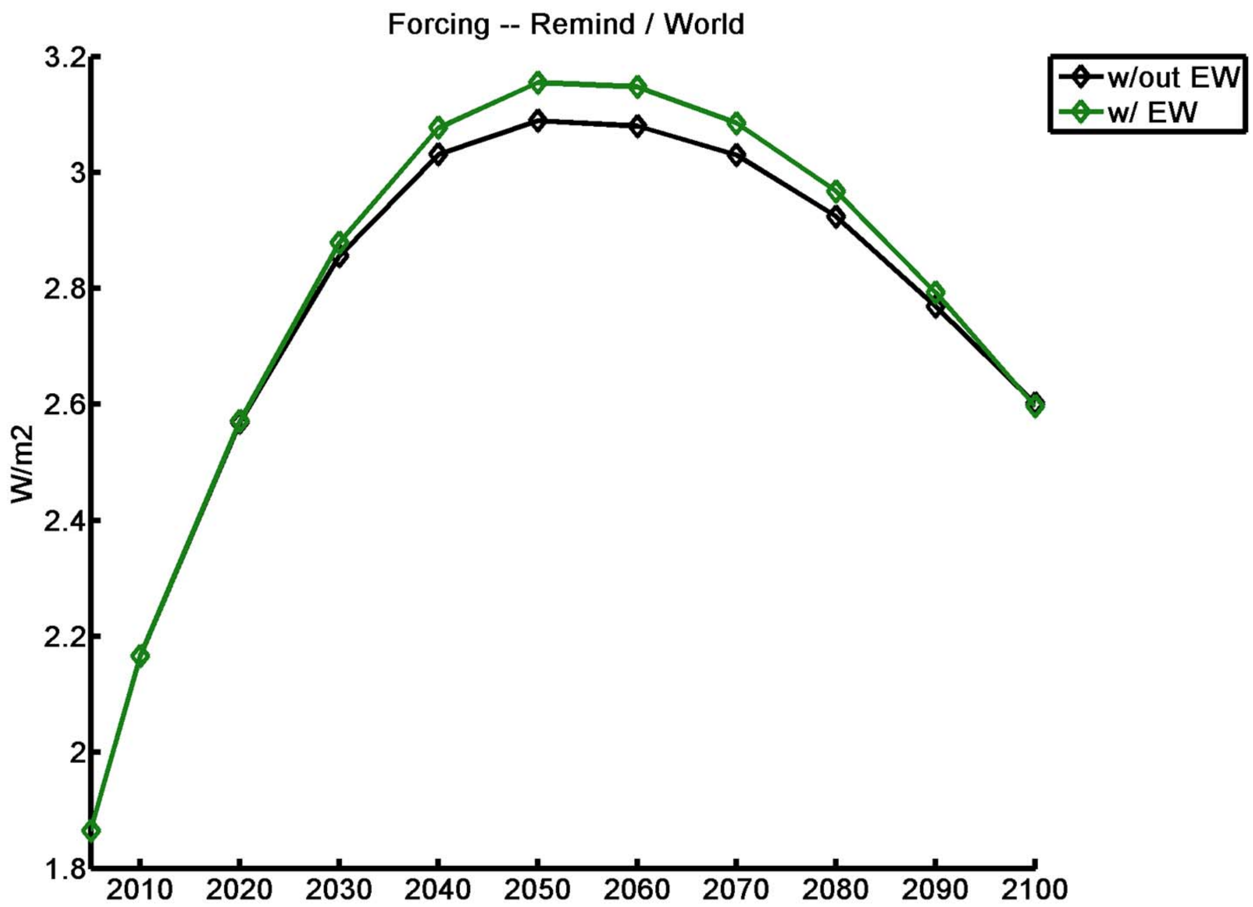
Fossil fuel emissions



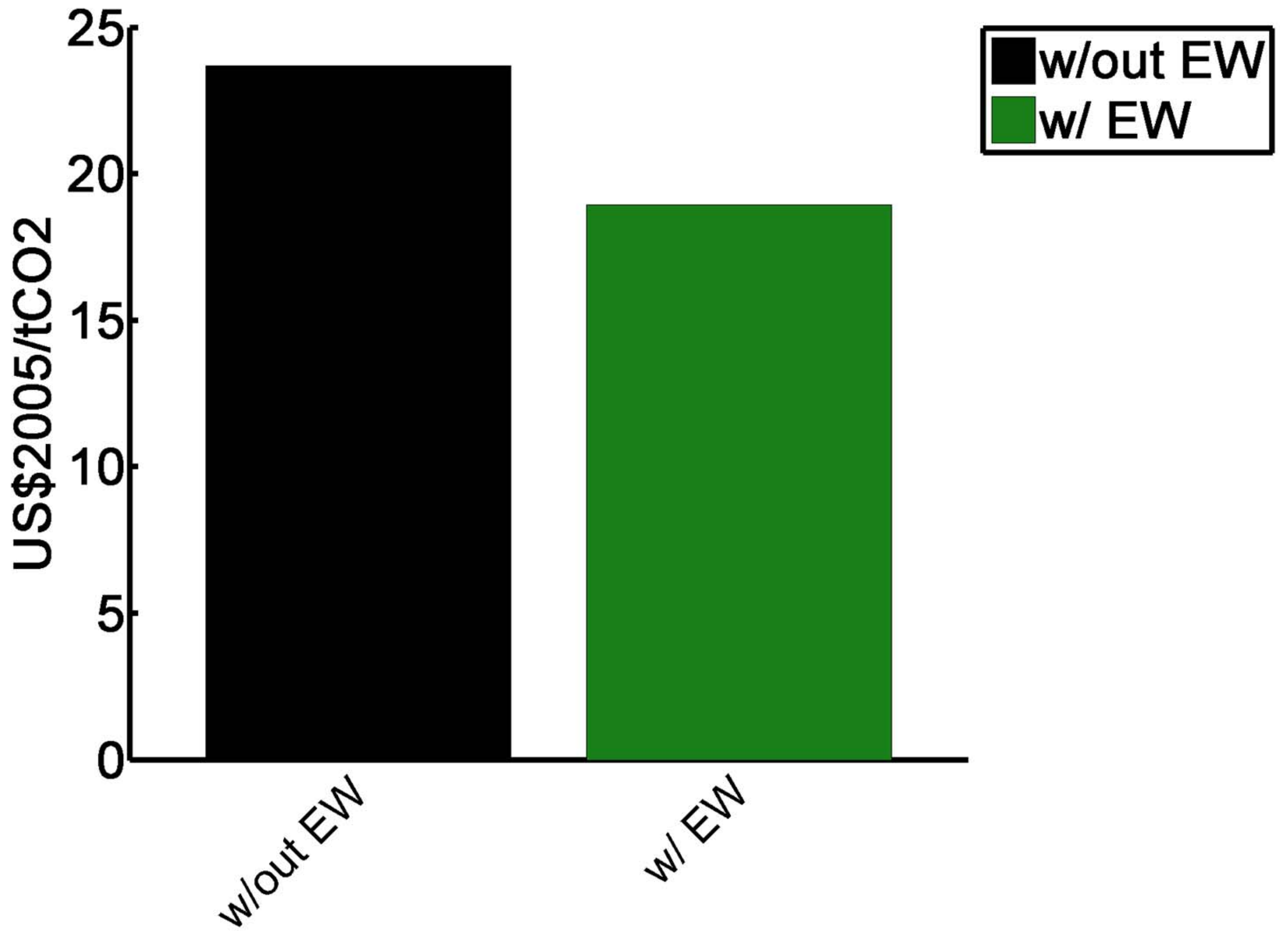
Total CO2 emissions



Radiative forcing



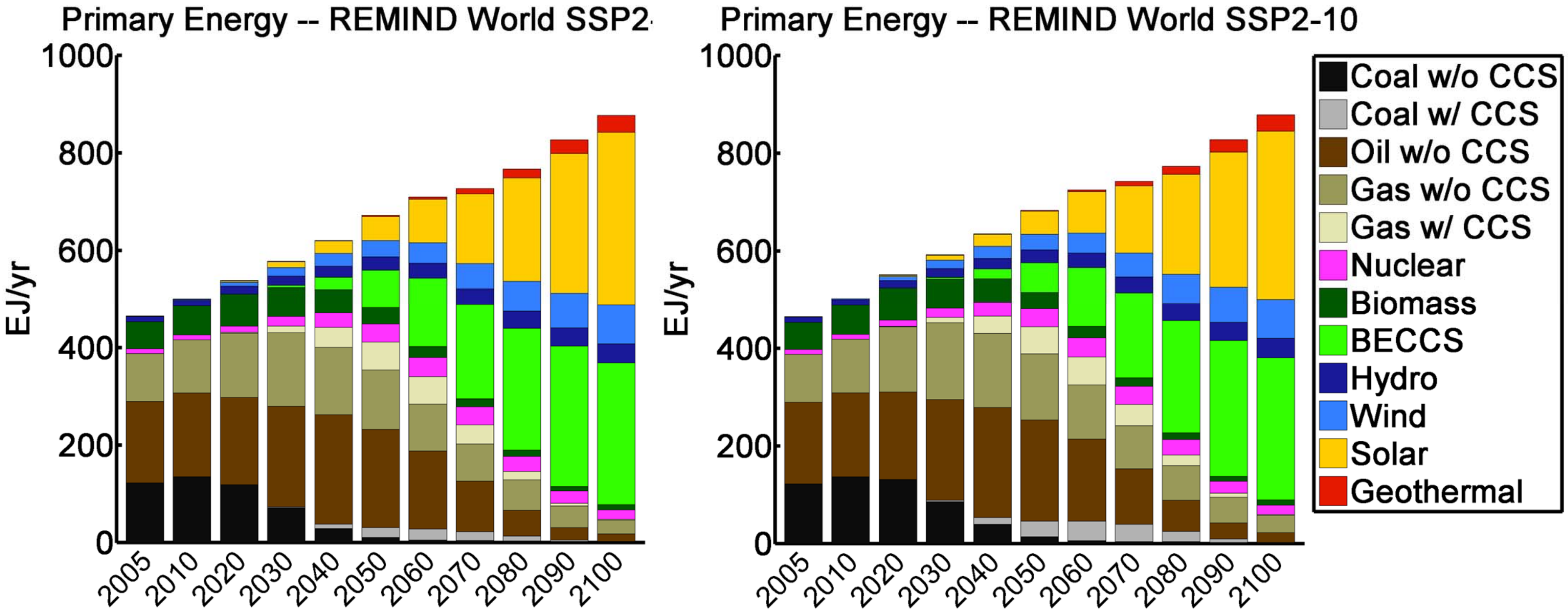
Carbon price in 2020



Primary energy mix

Without EW

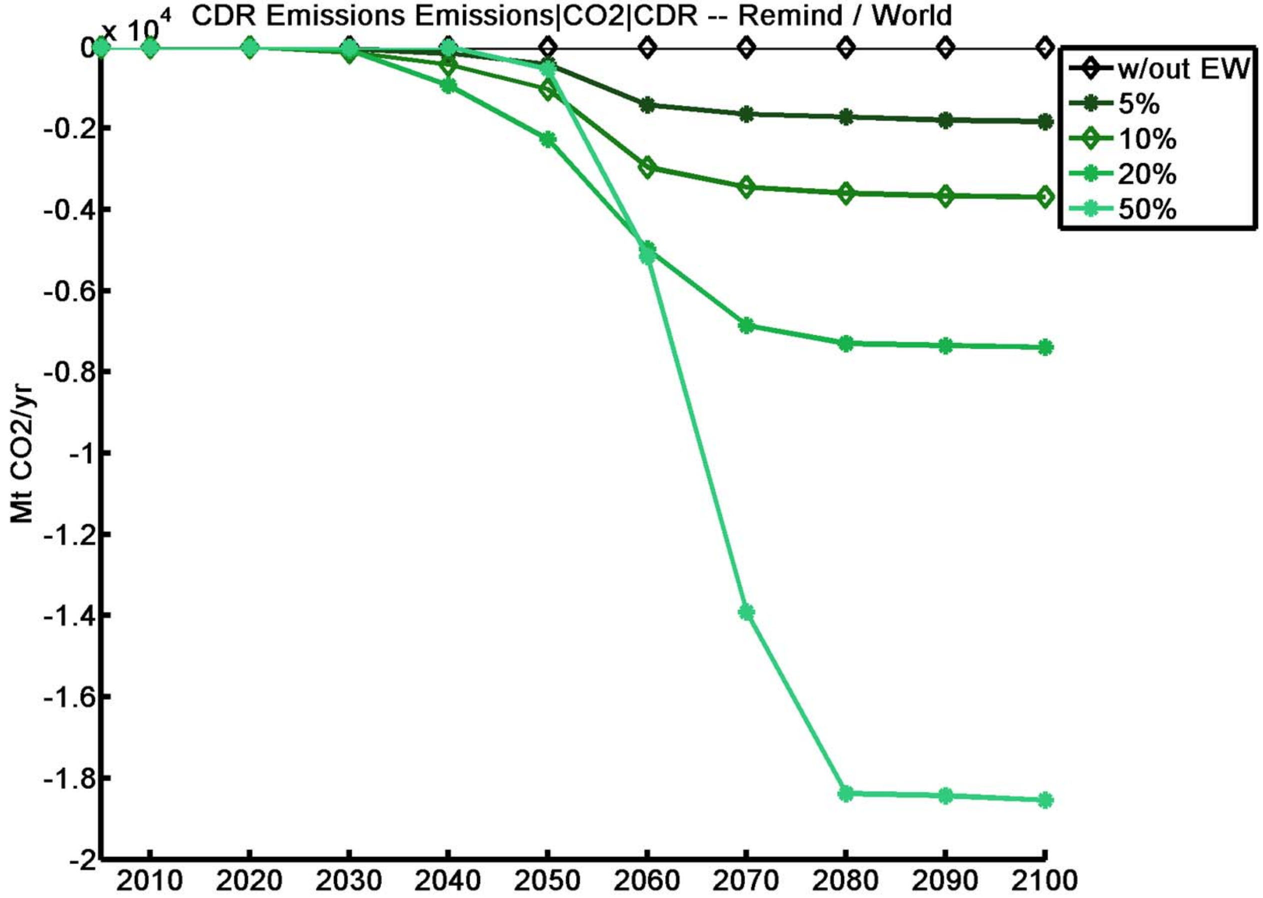
With EW



Scenarios

Limitations	Grain size [µm]	Weathering rate [% / yr]
Lower limit for validitiy of relations between grain size, weathering rate, energy input	2	50
	6	20
Current limit of technical feasibility?	10	14
Capital costs may increase disproportionately	20	10
Technically already feasible	50	5

Negative emissions



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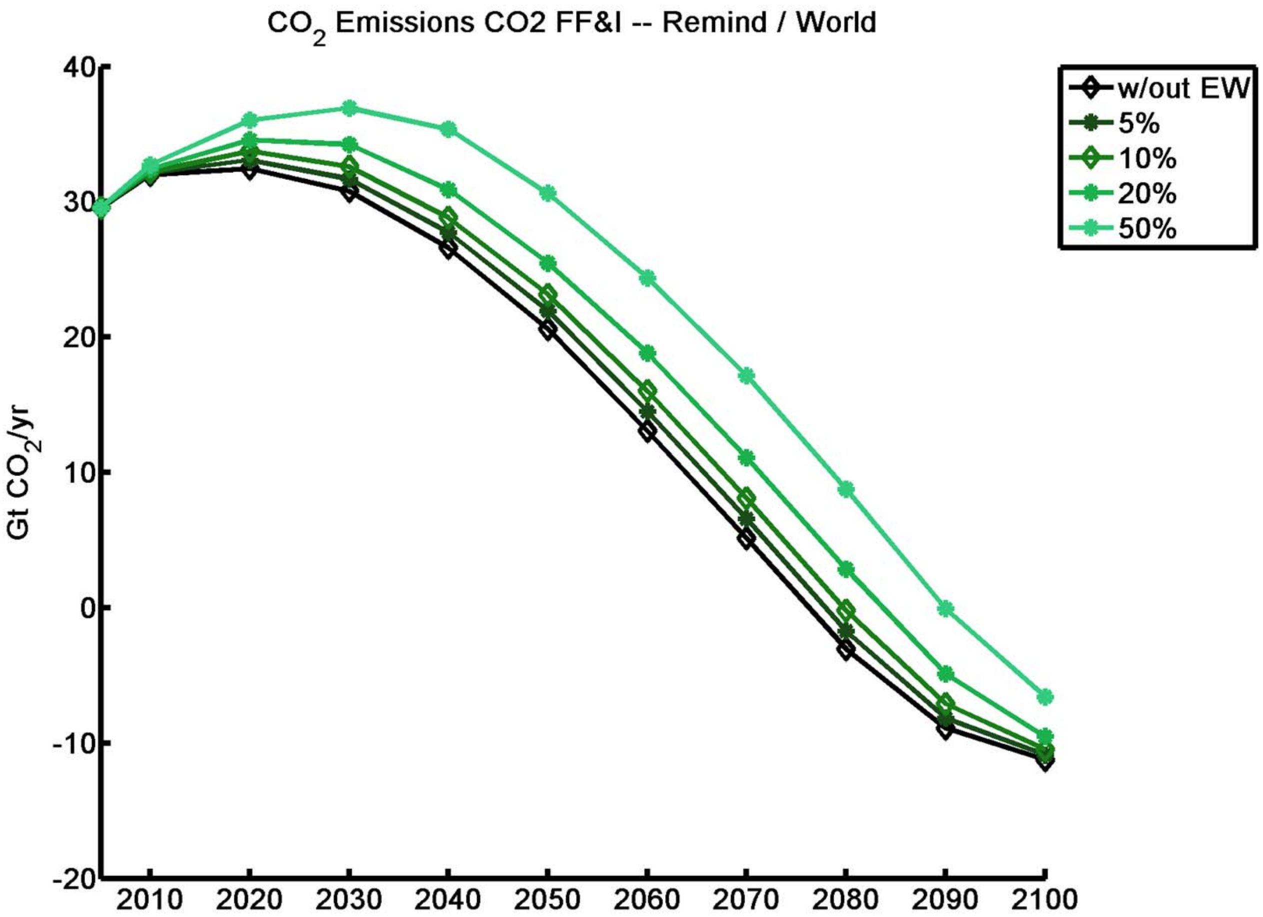
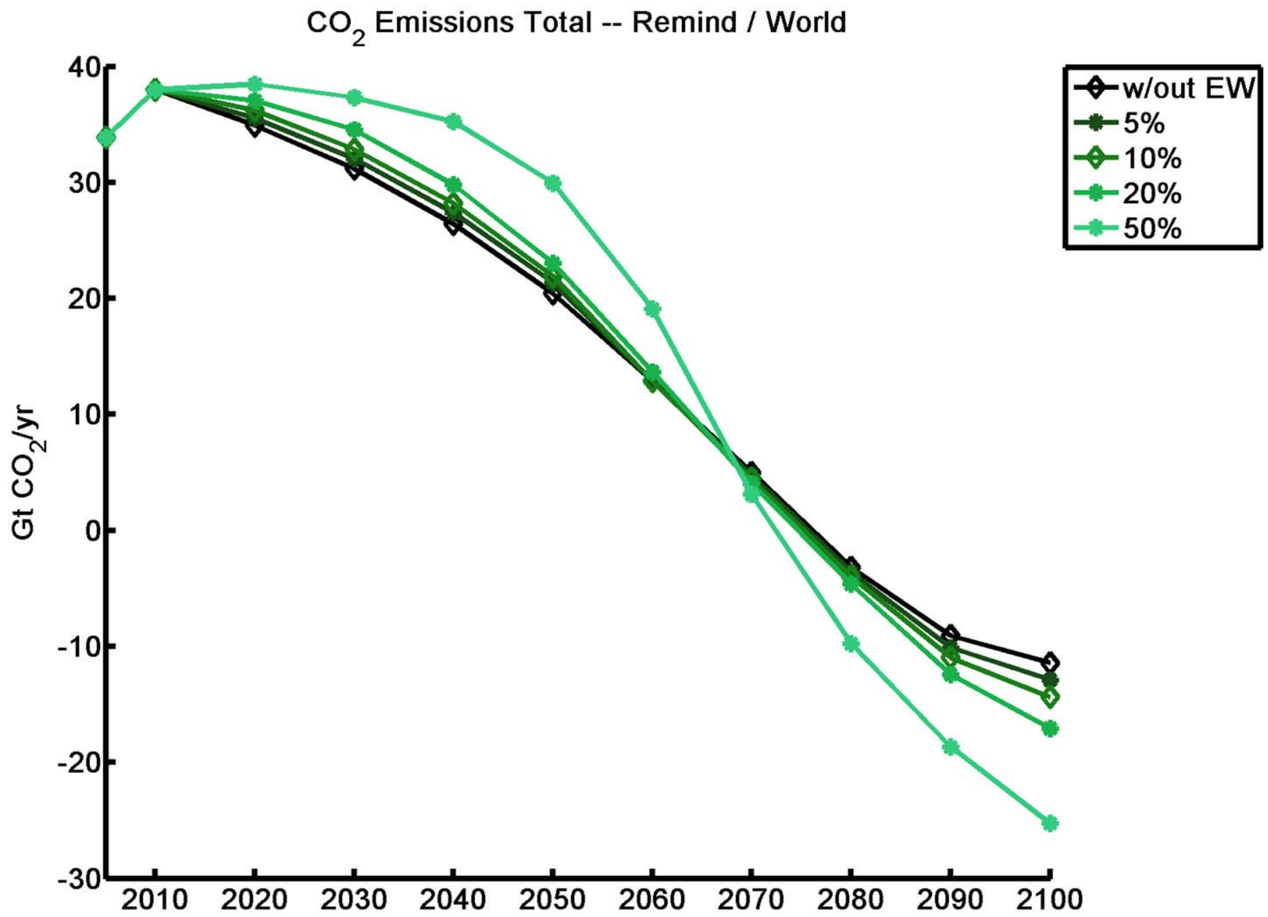


Total CO2 emissions



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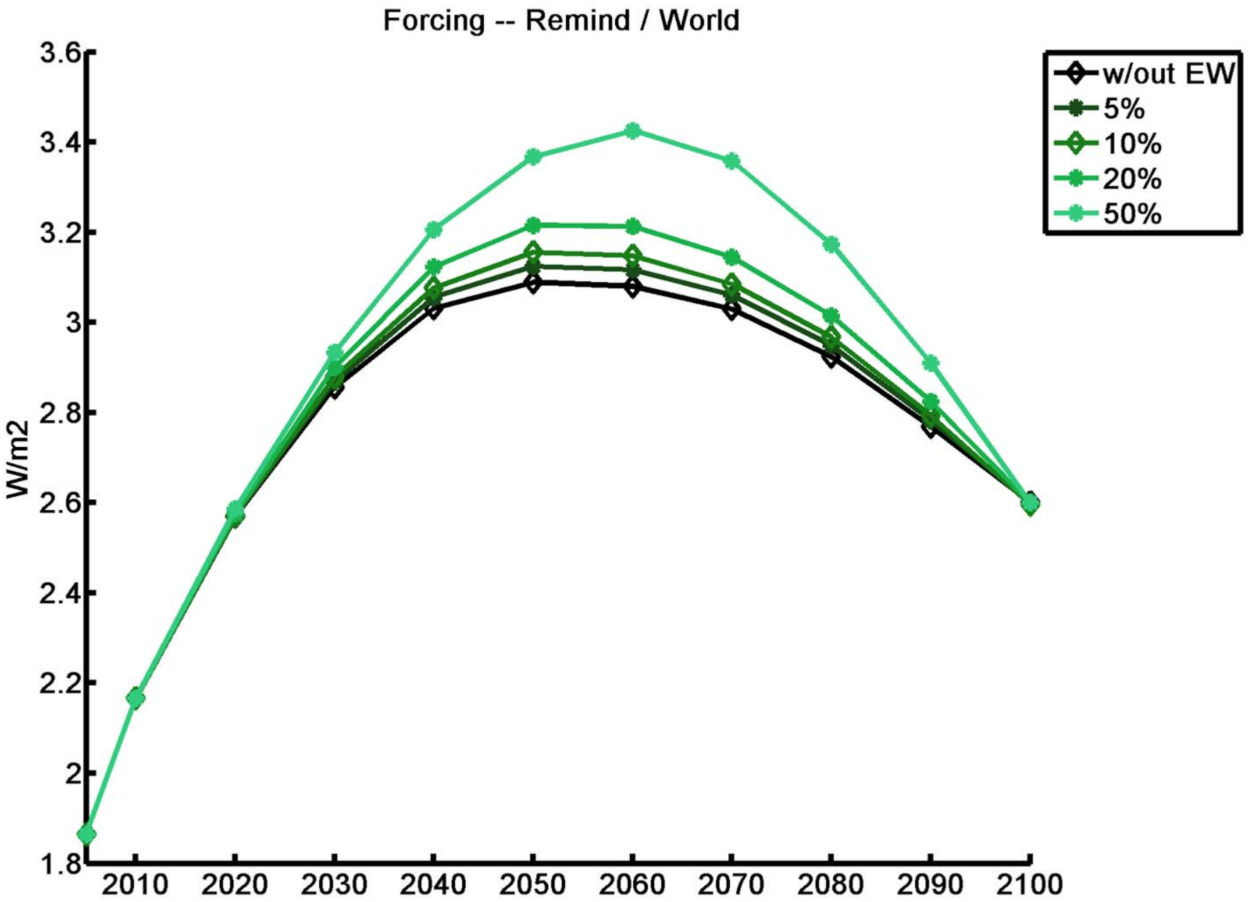
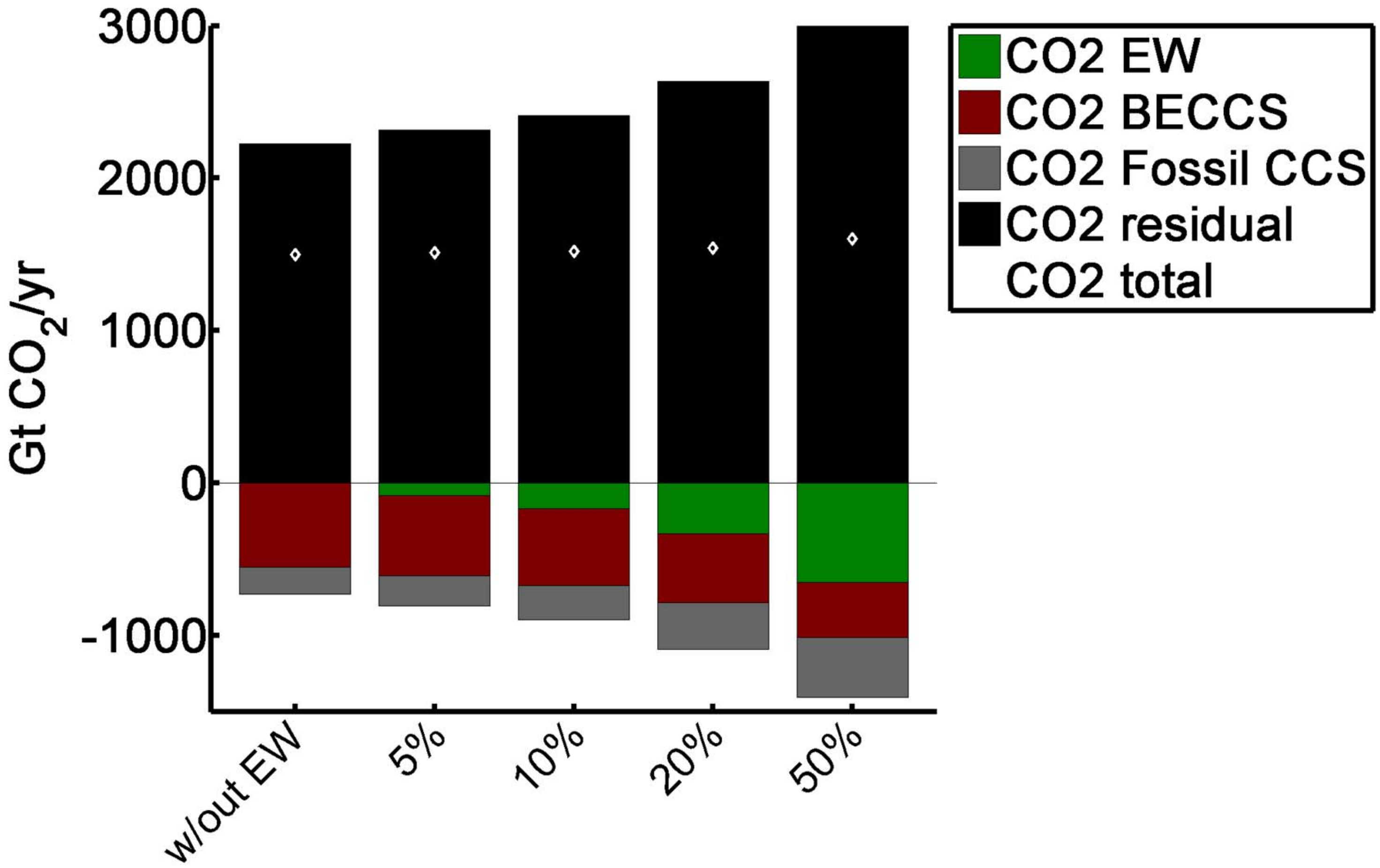
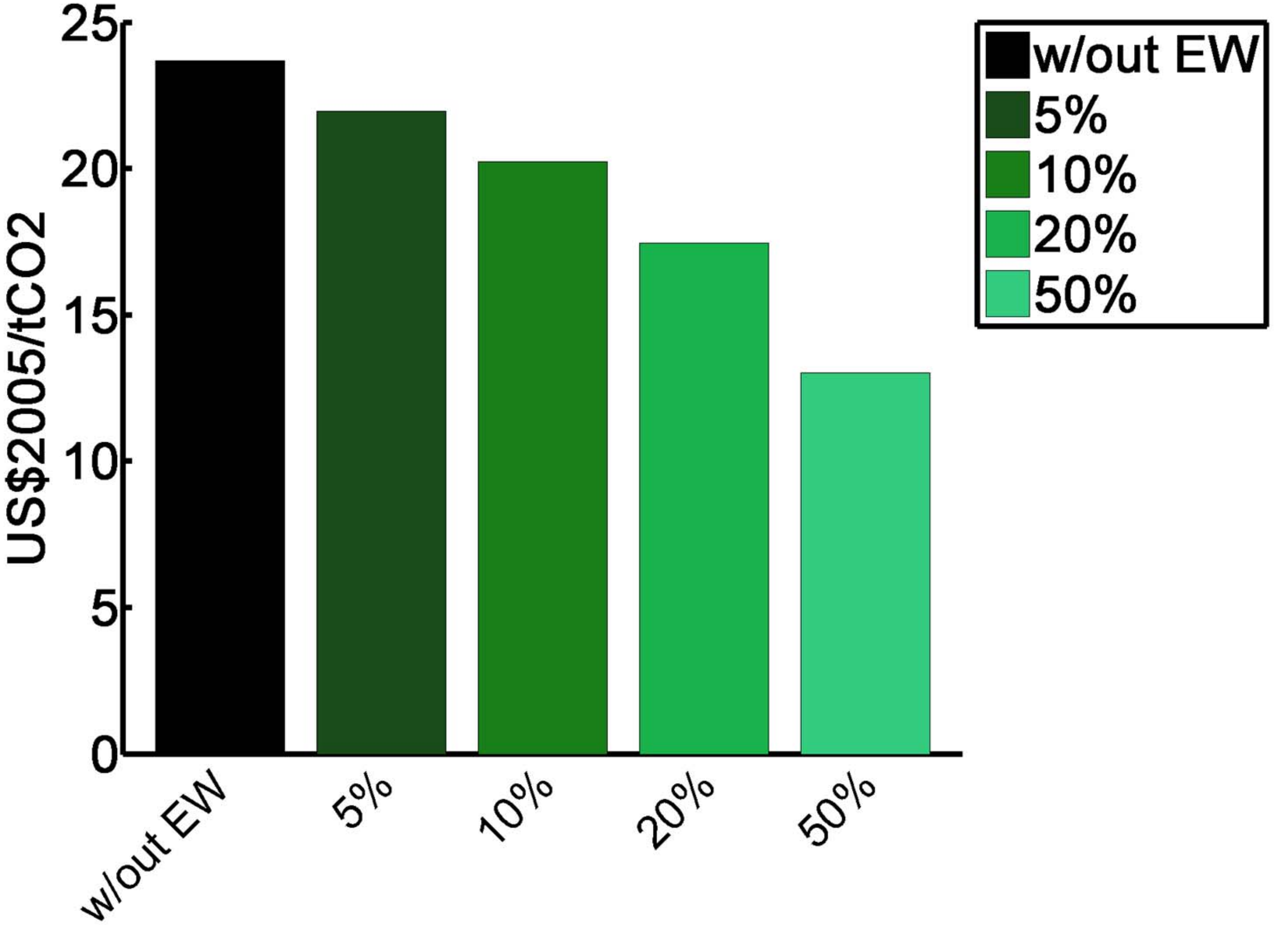


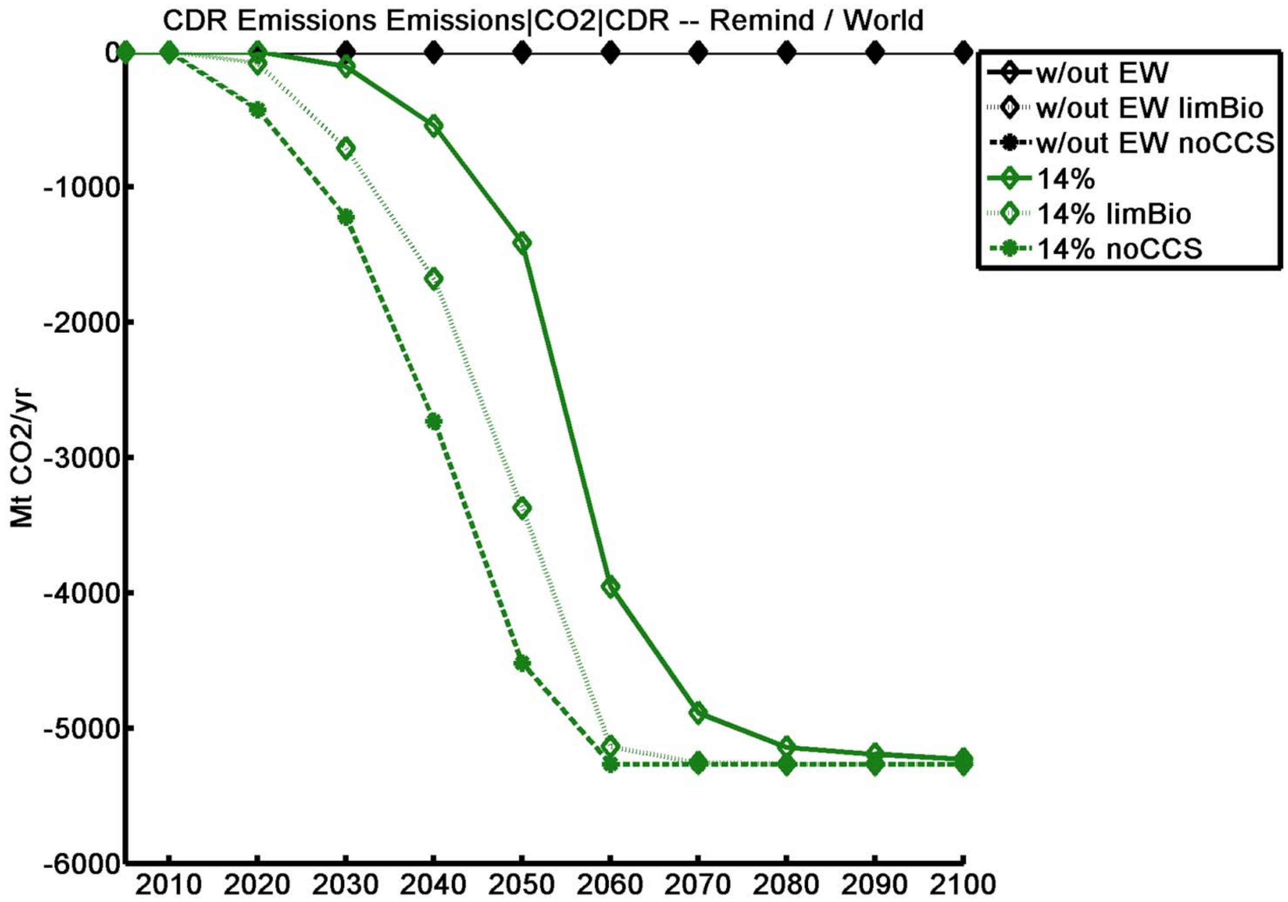
Change of carbon pools until 2100



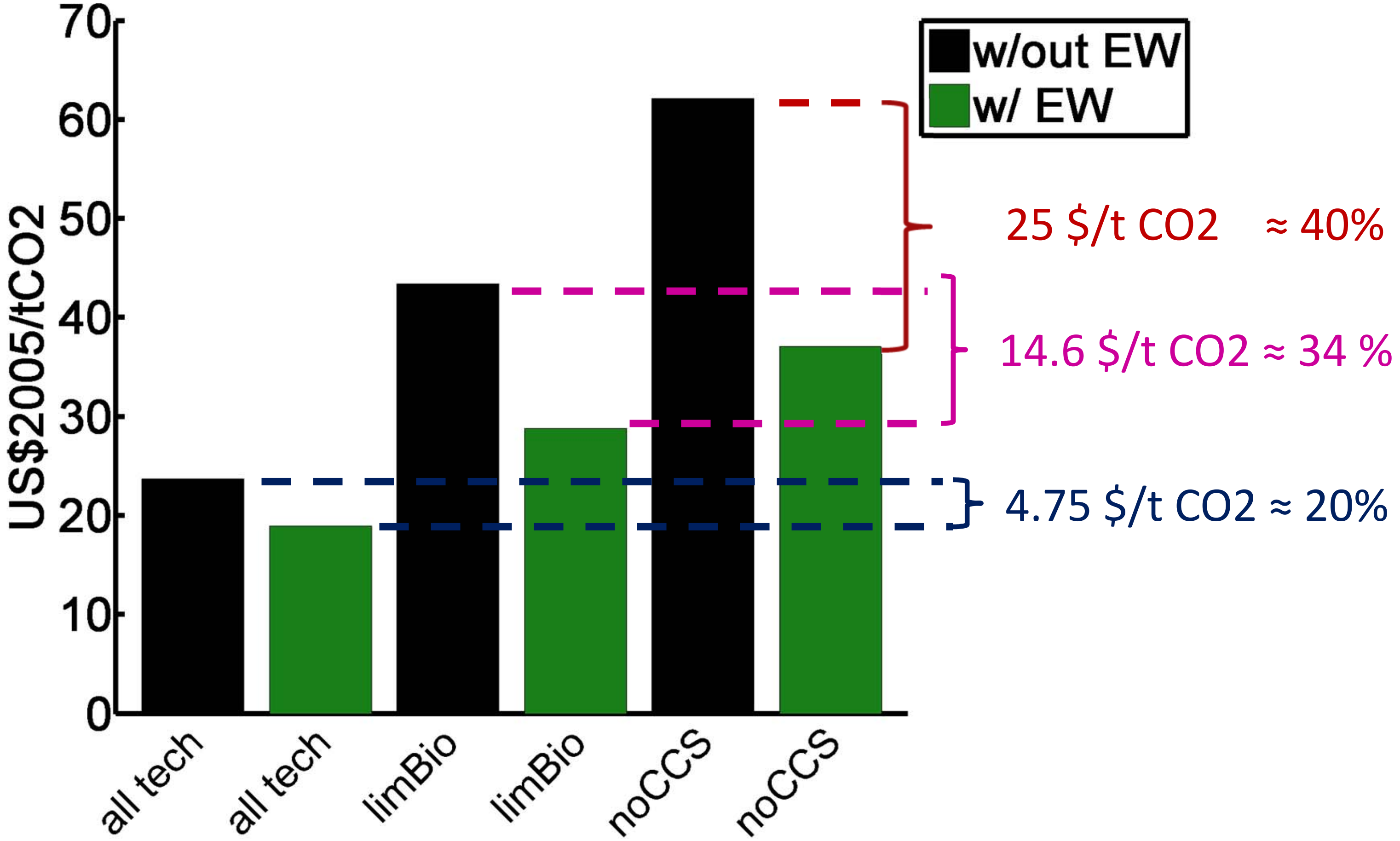
Carbon price in 2020



Negative emissions



Carbon price in 2020



Summary

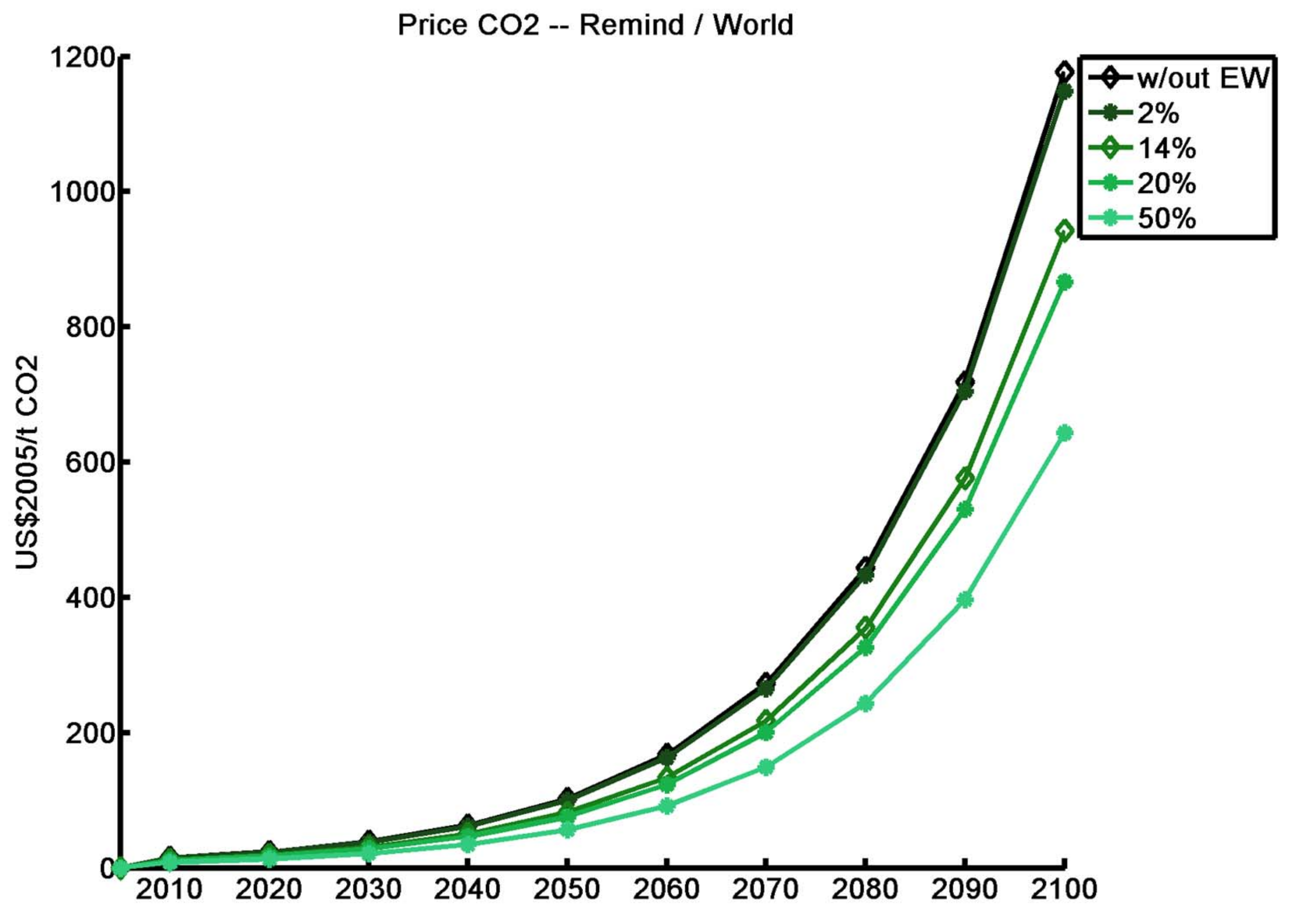
Grain size

- **Smaller grain size lead to higher profits per area**
- **Smaller grain size leads to higher potential**
- **Limited by technical feasibility, disproportionate cost increase**

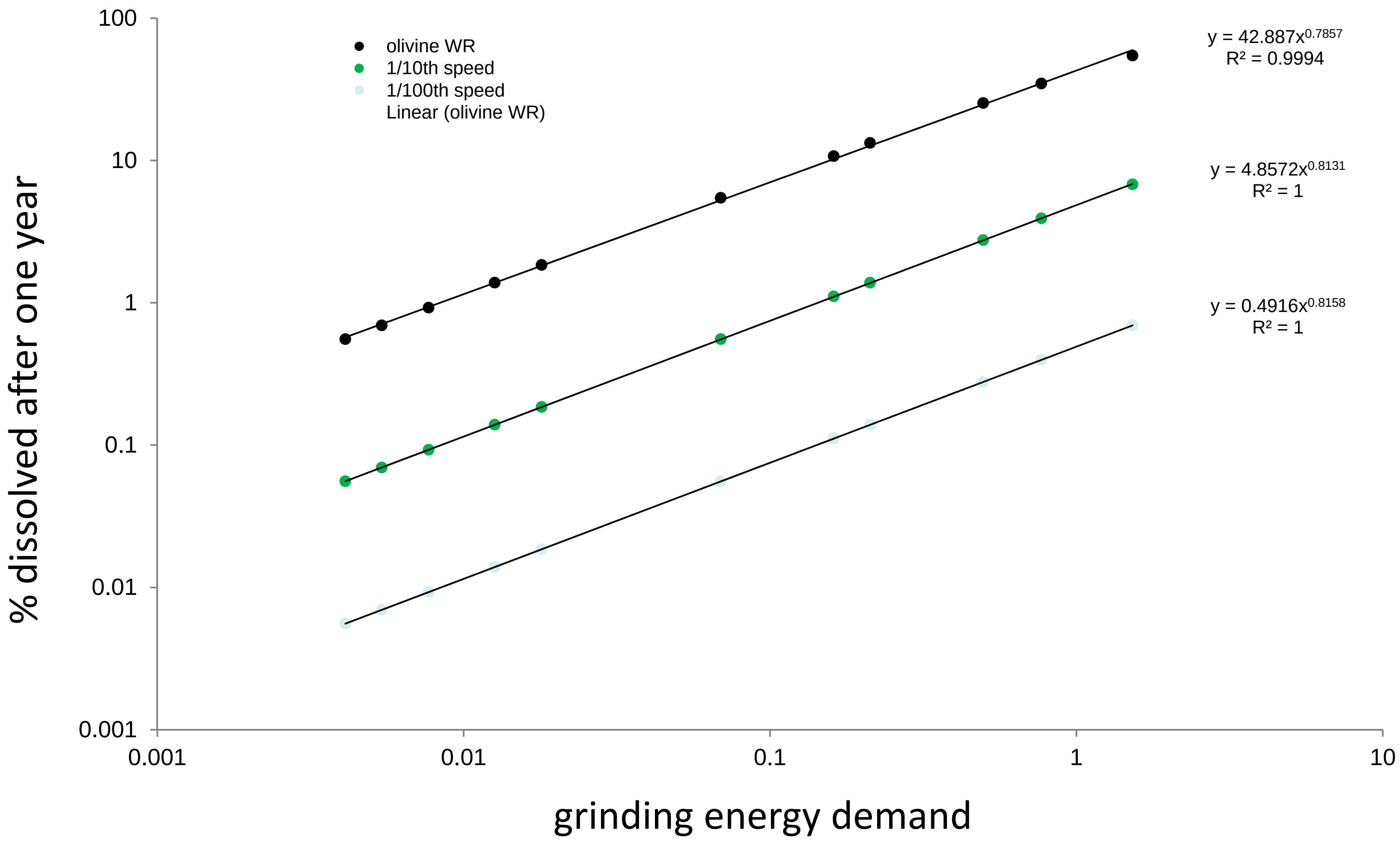
Integrated Assessment

- **Availability of EW reduces carbon price – partial substitute to other mitigation measures**
- **EW especially valuable if bioenergy is limited or CCS is not available**

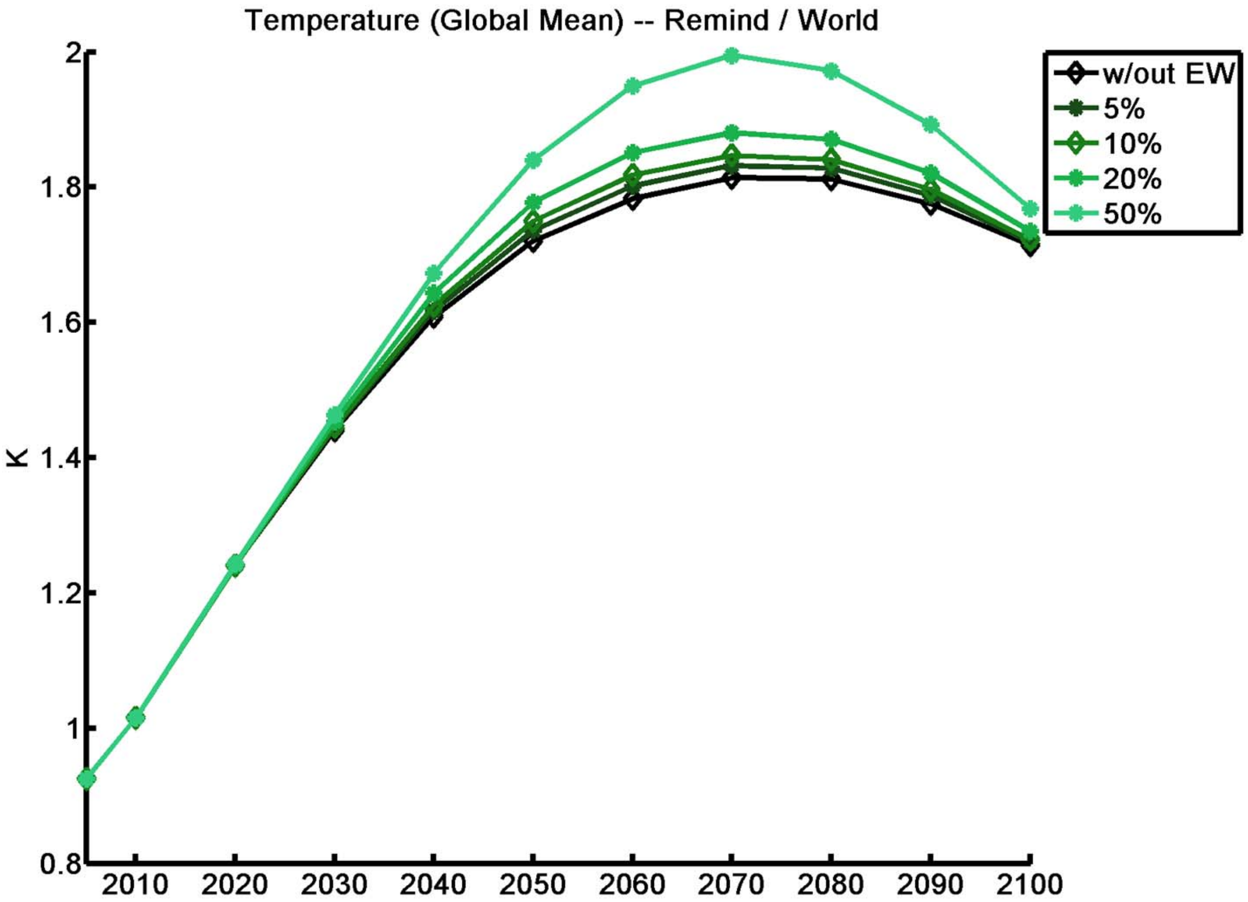
Thank you!


Price CO2 -- Remind / World
US$2005/t CO2
0
200
400
600
800
1000
1200
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
w/out EW
2%
14%
20%
50%

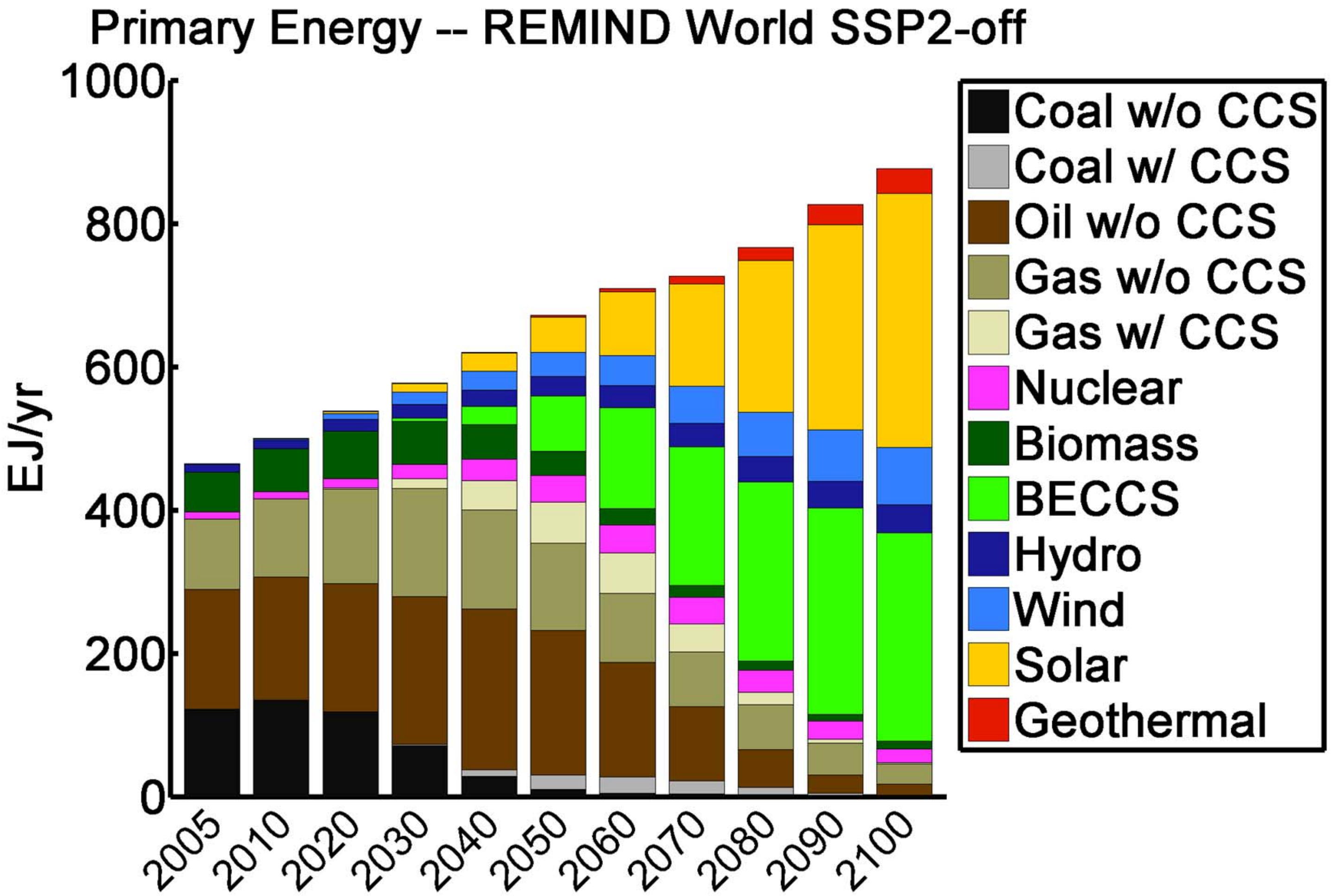
Carbon removal rate vs. Energy input



Temperature



Primary energy mix – no EW



Primary energy mix – with EW