FONDAZIONE ENI ENRICO MATTEI

New generation electricity networks and Climate Change: the economic potential of national and trans-national Super-Grids powered by Concentrated Solar Power

Elena C. Ricci

Università degli Studi di Milano and Fondazione Eni Enrico Mattei

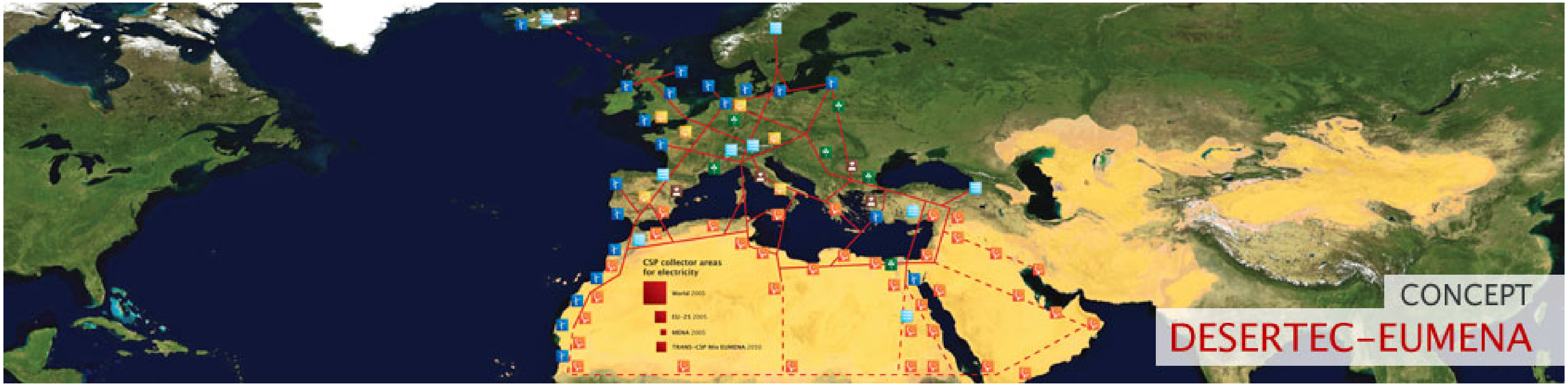
Joint work with Emanuele Massetti

FEEM, Milan 10 February 2011

Introduction

- New mitigation options look at the reingeneering of the electric power grid:
  - ➢ Super-Grids and Smart-Grids

- Super-Grids:
  - ➢ **connect** inter-regional electric power systems (smooth D&S variations)
  - ➢ facilitate **trade** among regions (efficiency)
  - ➢ allow to take advantage of **sources distantly located from the demand** (losses).



Modelling the Super-Grid

- We model the SG as:
  - ➢ HVDC cables
  - ➢ 2 converter stations
  - ➢ No change in national AC power grid

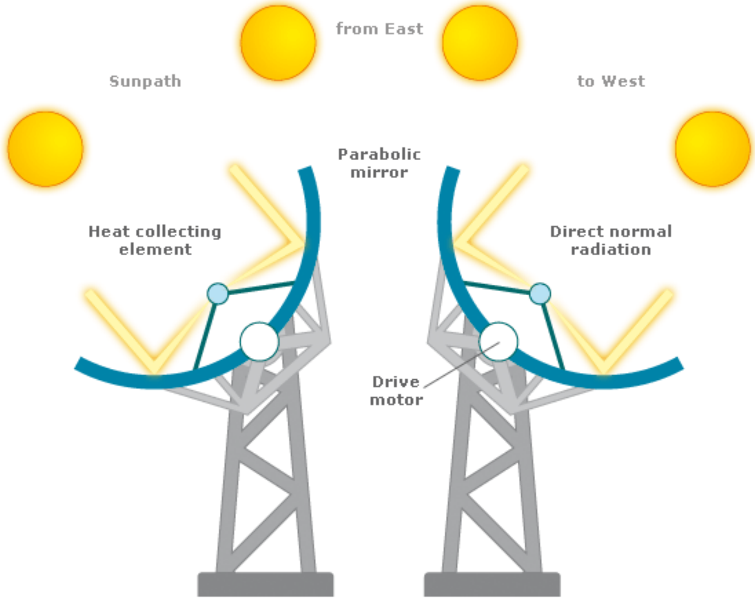
HVDC

- Transmission losses
- Submarine and underground cables
- Greater control over power transfers
- Cable footprint
- Converter stations

Modelling the Super-Grid

- SG may transmit electricity from any source
- Renewable energy most interesting case

- We focus on Concetrated Solar Power (CSP)
  - ➢ Parabolic troughs



CSP

- Heat storage
- Suitable for base-load
- Decreasing costs

Parabolic Troughs vs other CSP

- Commercially proven
- Modular
- Good land use factor
- Lowest demand for material

CSP powered Super-Grid in WITCH

- We allow CSP generation
  - MENA, USA, China

Power generation capacity in CSP accumulates according to the following function:

$$K_{CSP}(n,t+1) = K_{CSP}(n,t)(1-\delta_{CSP}) + \frac{I_{CSP}(n,t)}{SC_{CSP}(n,t)}$$

CSP investment costs are endogenously calculated depending:
- on cumulative world capacity in CSP power
- on regional expantion at each time period.

$$SC_{CSP}(n,t+1) = SC_{CSP}(n,t_0)\cdot \frac{TK_t}{TK_0}^{-(\alpha)} \cdot \left(1 + \left(\frac{\left(\frac{I_{CSP}(n,t+1)}{SC_{CSP}(n,t+1)} \right)}{\beta} \right)^{\gamma} \right)$$

$$TK_{CSP}(n,t+1) = TK_{CSP}(n,t) + \frac{I_{CSP}(n,t)}{SC_{CSP}(n,t)}$$

FONDAZIONE ENI ENRICO MATTEI

CSP powered Super-Grid in WITCH

- To be able to consume this electricity there is the need for transmission
  - USA, CINA
  - MENA

$$EL_{CSP,prod}(n,t) = \min\left\{\mu_{n,CSP} K_{CSP}(n,t); \theta_{CSP} O\&M_{CSP}(n,t); \mu_{n,grid} K_{grid}(n,t); \theta_{grid} O\&M_{grid}(n,t)\right\}$$

$$K_{grid}(n,t+1) = K_{grid}(n,t)(1-\delta_{grid}) + \frac{I_{grid}(n,t)}{SC_{grid}(n,t)}$$

$$SC_{grid}(n,t) = SC_{grid}(n,t_0)$$

$$C(n,t) = Y(n,t) - I_c(n,t) - \sum_w p_w Z_w(n,t) - I_{CSP}(n,t) - I_{grid}(n,t) - O\&M_{CSP}(n,t) - O\&M_{grid}(n,t)$$

Fondazione Eni Enrico Mattei

EU-MENA CSP Trade

MENA has also the option to export CSP electricity to Western and Eastern Europe through a SG that connects the three regions.

$$EL_{CSP,X}(n,t) = \min\left\{\mu_{n,CSP} K_{CSP}(n,t); \theta_{CSP} O\&M_{CSP}(n,t); \mu_{n,X} K_{grid,X}(n,t); \theta_{grid} O\&M_{grid,X}(n,t)\right\}$$

$$EL_{CSP,prod}(n,t) = EL_{CSP}(n,t) + EL_{CSP,X}(n,t)$$

With: $EL_{CSP,X}(n,t) > 0$ in exporting regions
$EL_{CSP,X}(n,t) < 0$ in importing regions
$EL_{CSP,X}(n,t) = 0$ in regions that are not connected to an international electricity grid.

The introduction of the trade of electricity between Europe and MENA introduces a new interaction channel between the three regions: the market of CSP electricity.

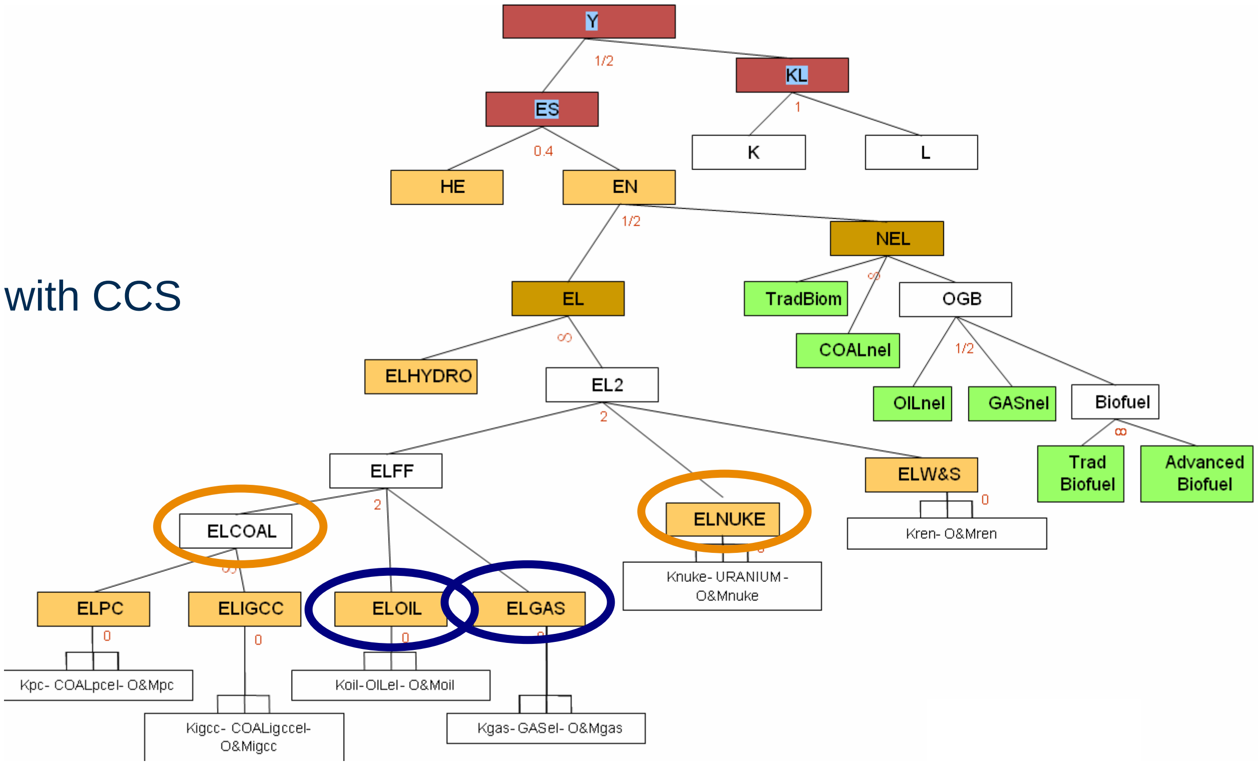
Western and Eastern Europe have the possibility to import CSP electricity from MENA,
paying the price that stabilizes the market, that is:

$$P_{CSP}(t) \quad \Big| \quad \sum_n EL_{CSP,X}(n,t) = 0 \quad \forall t$$

$$Y(n,t) = GY(n,t) - \sum_q p_q V_q(n,t) + EL_{CSP,X}(n,t) P_{CSP}(t)$$

CSP powered Super-Grid in WITCH

- CSP electricity can directly substitute:
  - Gas and Oil generation
    - MENA
  - Nuclear power and IGCC with CCS
    - USA
    - China
    - Western Europe
    - Eastern Europe



Fondazione Eni Enrico Mattei

Data

- CSP costs (parabolic through - 50 MW – 100% solar share – 7h thermal storage): Kaltschmitt M. (2007)
  - **Investment costs**
  - **Operation and maintenance costs**
  - **Thermal storage costs**

- Plant Efficiency:
  - **Direct Normal Radiation Data:** NASA Atmospheric Science Data Center (2010)
    - MENA: Sahara Region
    - USA: Arizona – Phoenix
    - China: Tibet - Xigaze
  - **Full load hours**: Trieb (2009)

- Costs for Super-Grid infrastructure (HVDC - 5 GW - +/- 800 kV): May (2005)
  - **Investment costs**
  - **Transmission losses**
  - **Terminal losses**
  - **Operation and maintenance costs**

  - **Distances**:
    - MENA: 3000 km (Czisch (2004), Trieb (2009), Bauer (2009));
    - USA: 577 km and 3447 km (Phoenix to Los Angeles or New York)
    - China: 2800 km (Xigaze to Beijing, Shanghai and Guangzhou)

Simulation Scenarios

- **Business as usual** ("Bau")
  no climate policy, i.e. no restriction on GHG emissions

- **Unconstrained Stabilization** ("Stab");

- **Constrained Stabilization with limit on Nuclear Power** ("NoNuke-Stab"),
  expansion of Nuclear Power that cannot exceed 2005 levels;

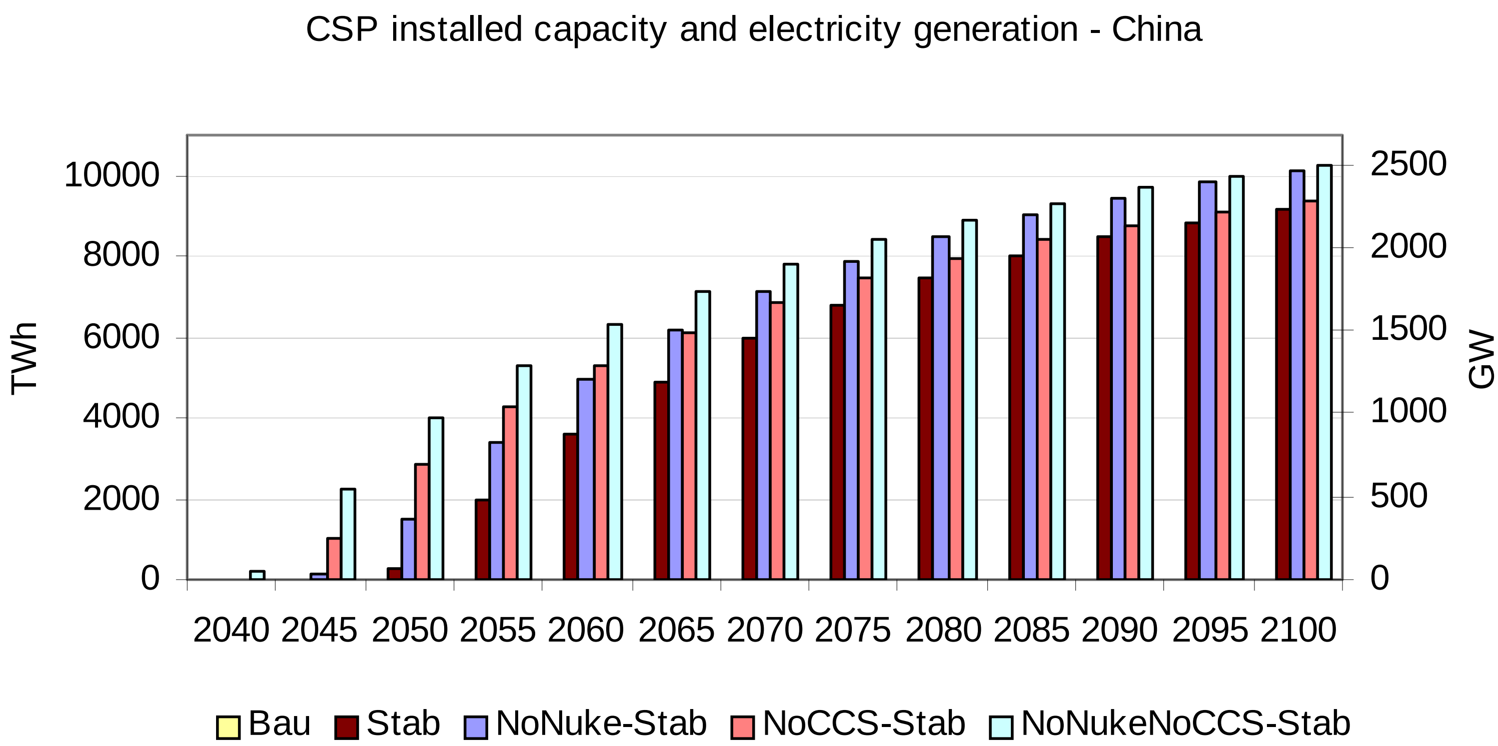
- **Constrained Stabilization with limit on CCS** ("NoCCS-Stab"),
  there is no possibility of Capturing and Storing CO_2 (CCS);

- **Constrained Stabilization with penetration limits on Nuclear power and CCS** ("NoNuke-NoCCS-Stab"),
  with both additional constraints on Nuclear power and CCS activities.

<u>Policy Scenarios:</u>

- **Stabilization target:** All GHG atmospheric concentration stabilised at 535ppm-CO_2eq by 2100
- **Stabilization instrument:** a world carbon market that equalizes marginal abatement costs worldwide. Carbon allowances are allocated according to the "Contraction and Convergence" scheme.

CSP deployment

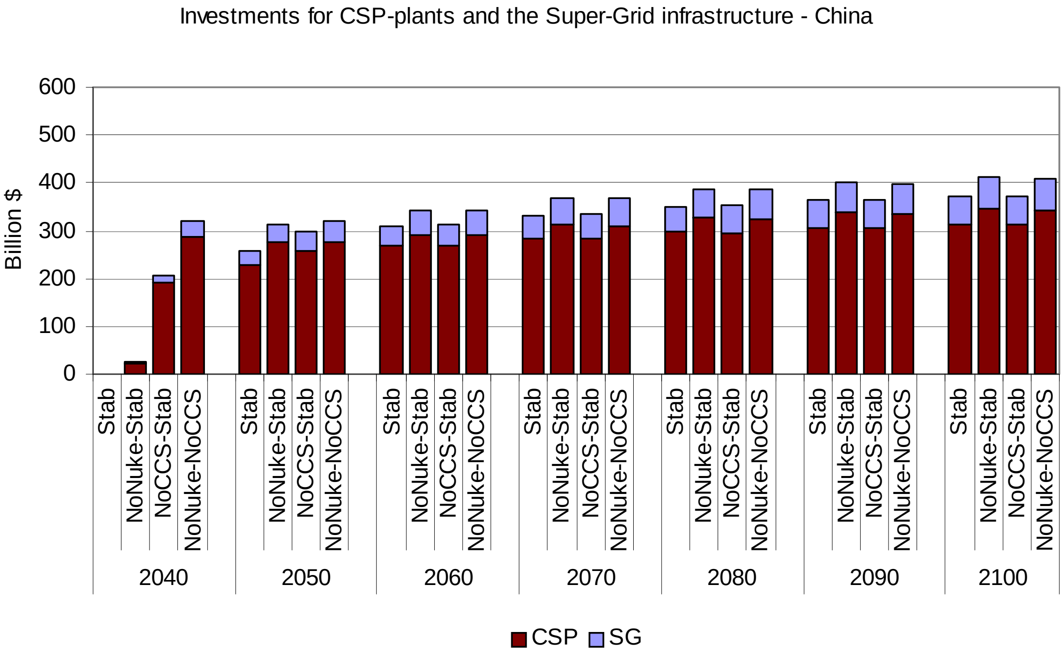


Note: CSP production is optimal from 2035-2040 or later

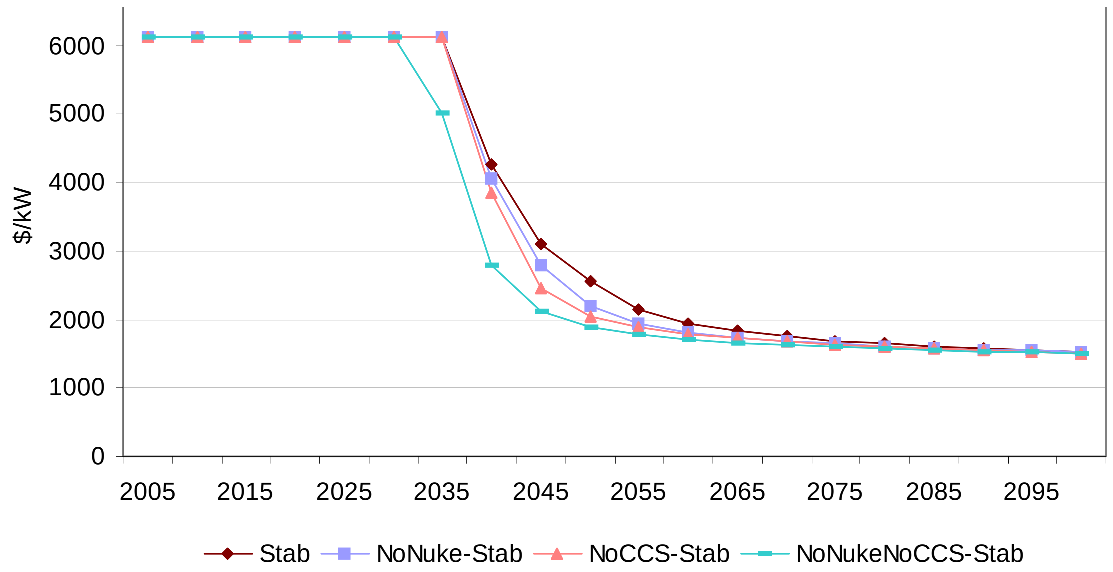
FONDAZIONE ENI ENRICO MATTEI

Investments

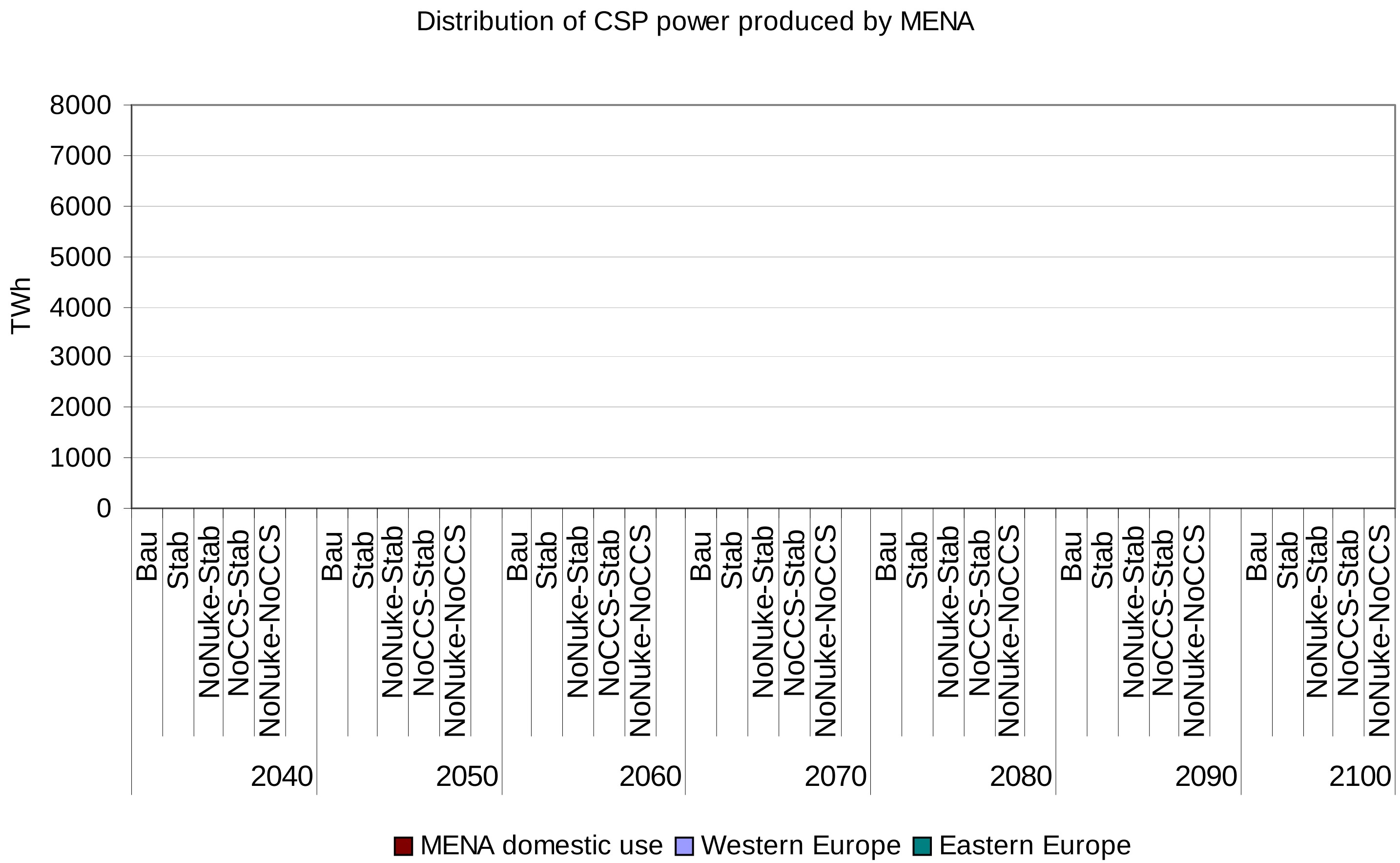
Necessary investments:



Investment cost - LbD effect
at world level

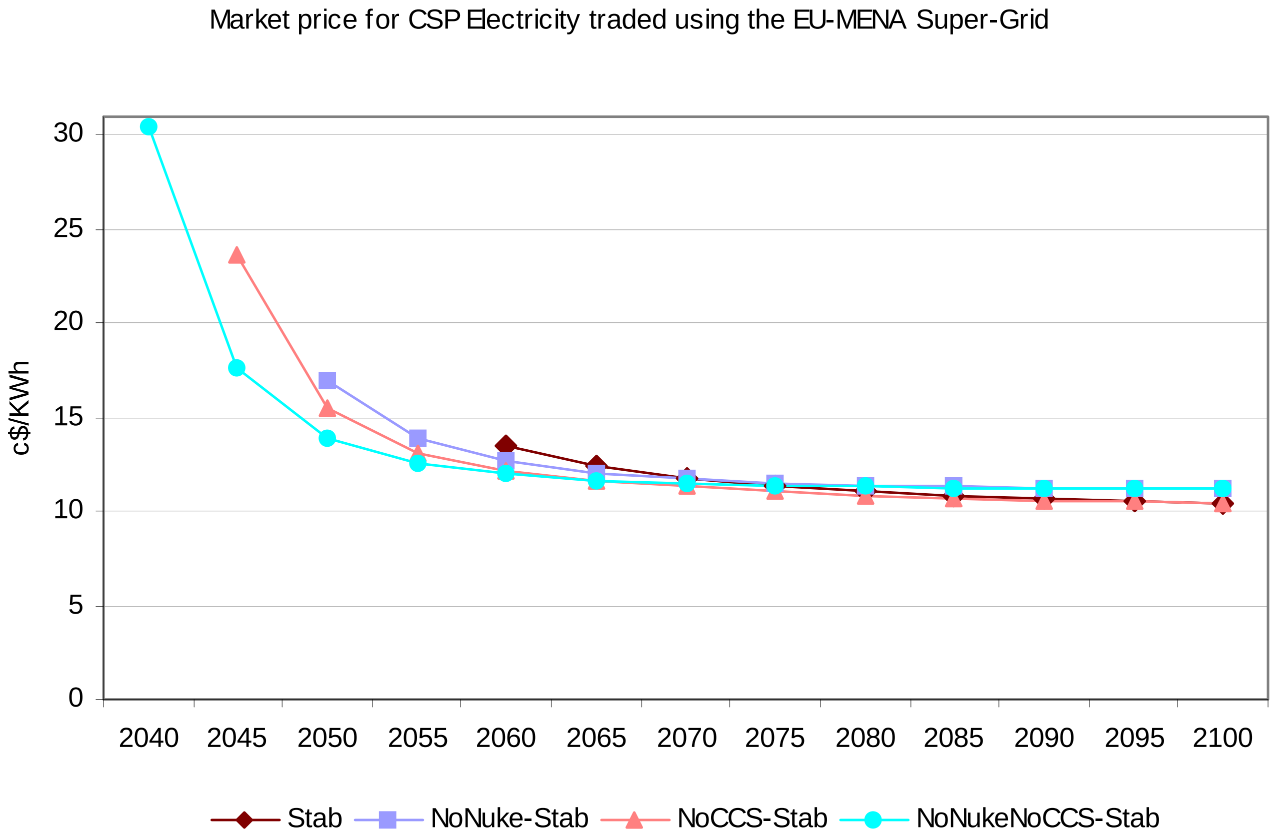


EU-MENA CSP-Electricity Trade



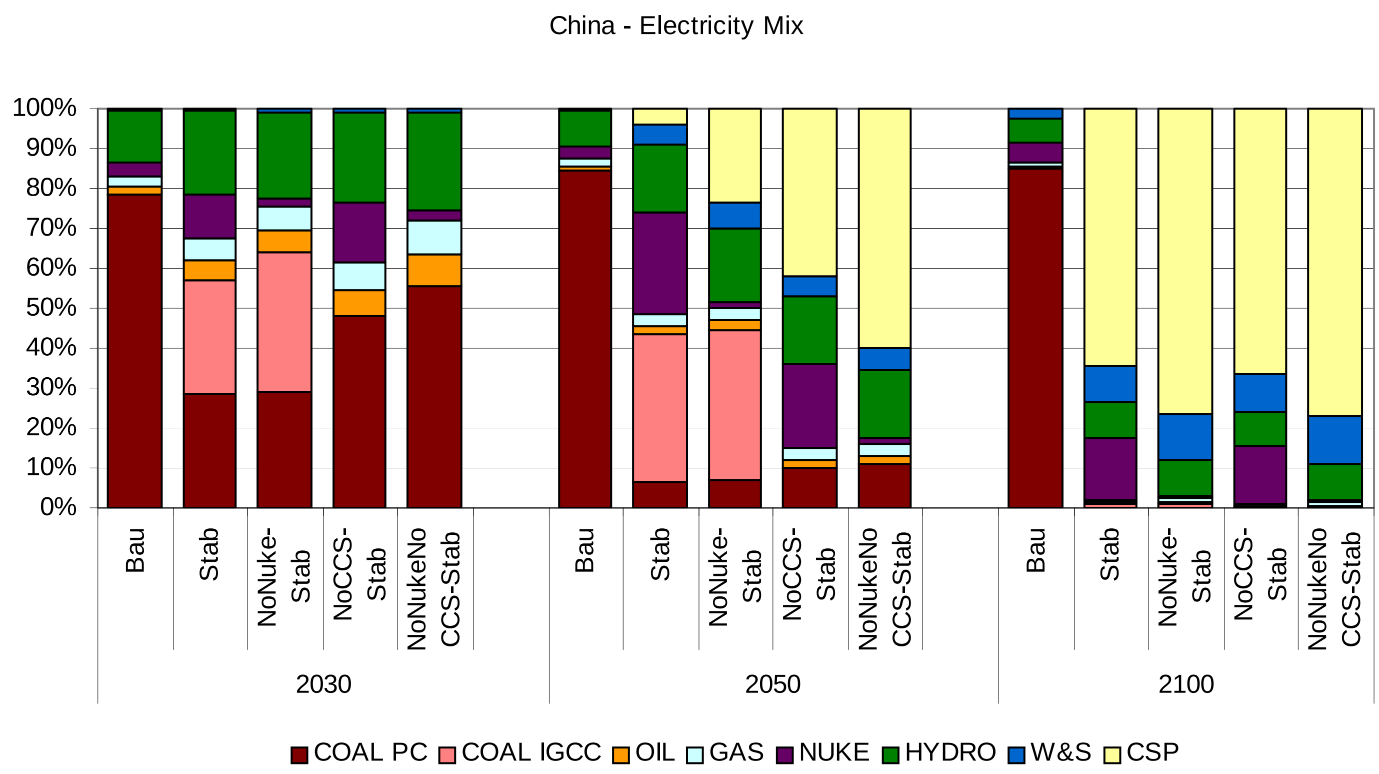
Note: CSP domestic consumption is high

Market Price for CSP Electricity



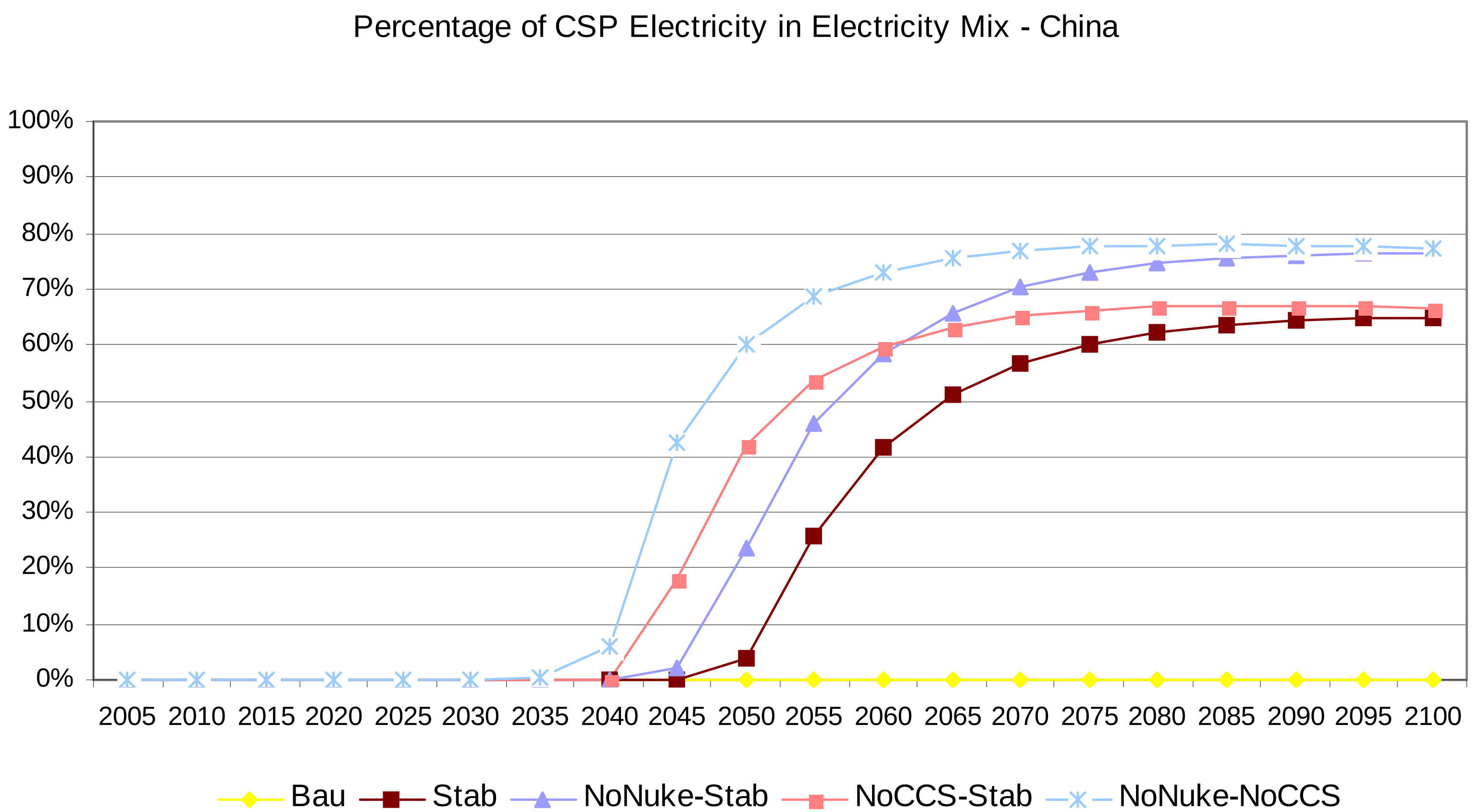
FONDAZIONE ENI ENRICO MATTEI

Electricity Mix



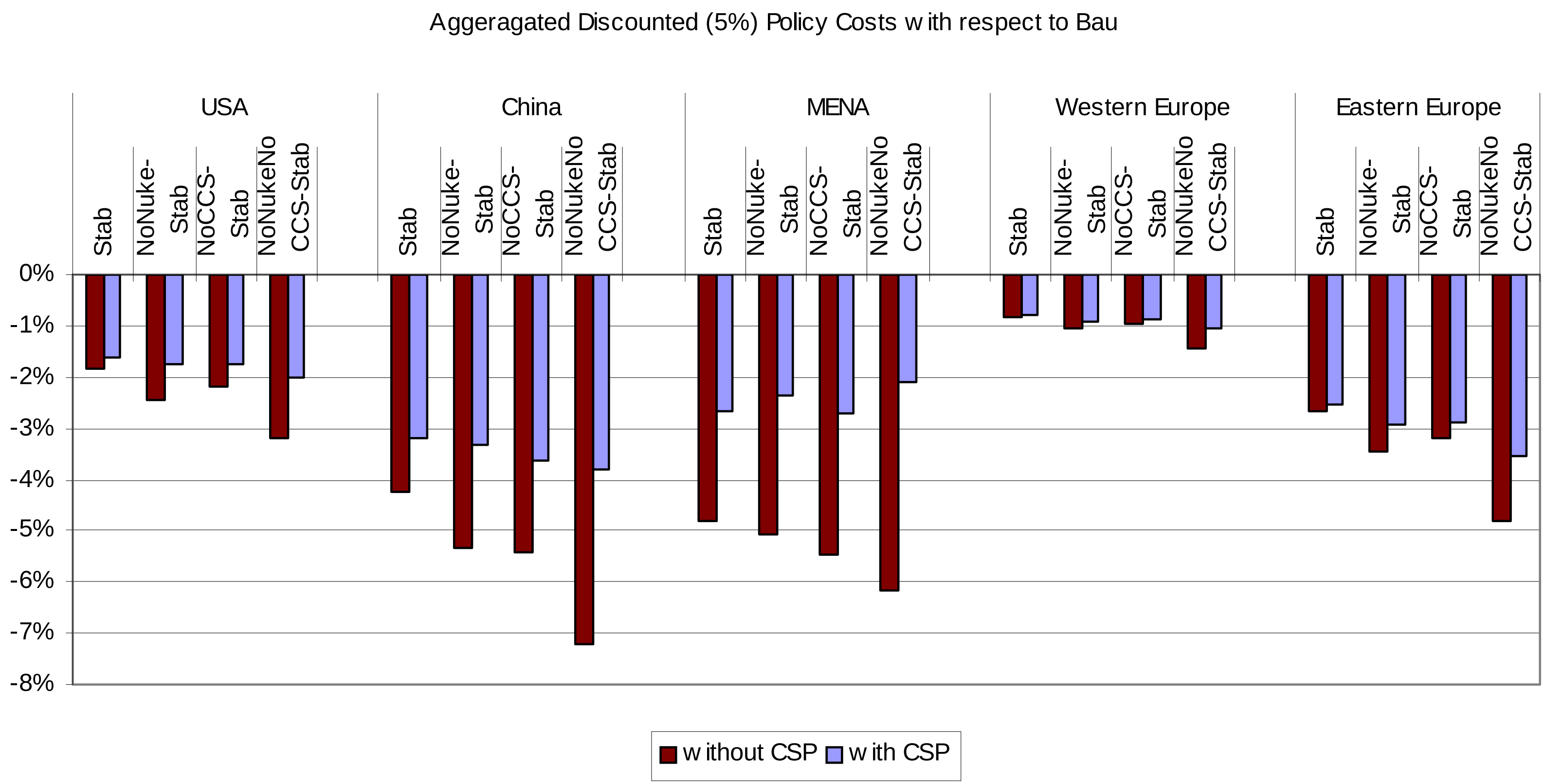
FONDAZIONE ENI ENRICO MATTEI

CSP penetration rates



FONDAZIONE ENI ENRICO MATTEI

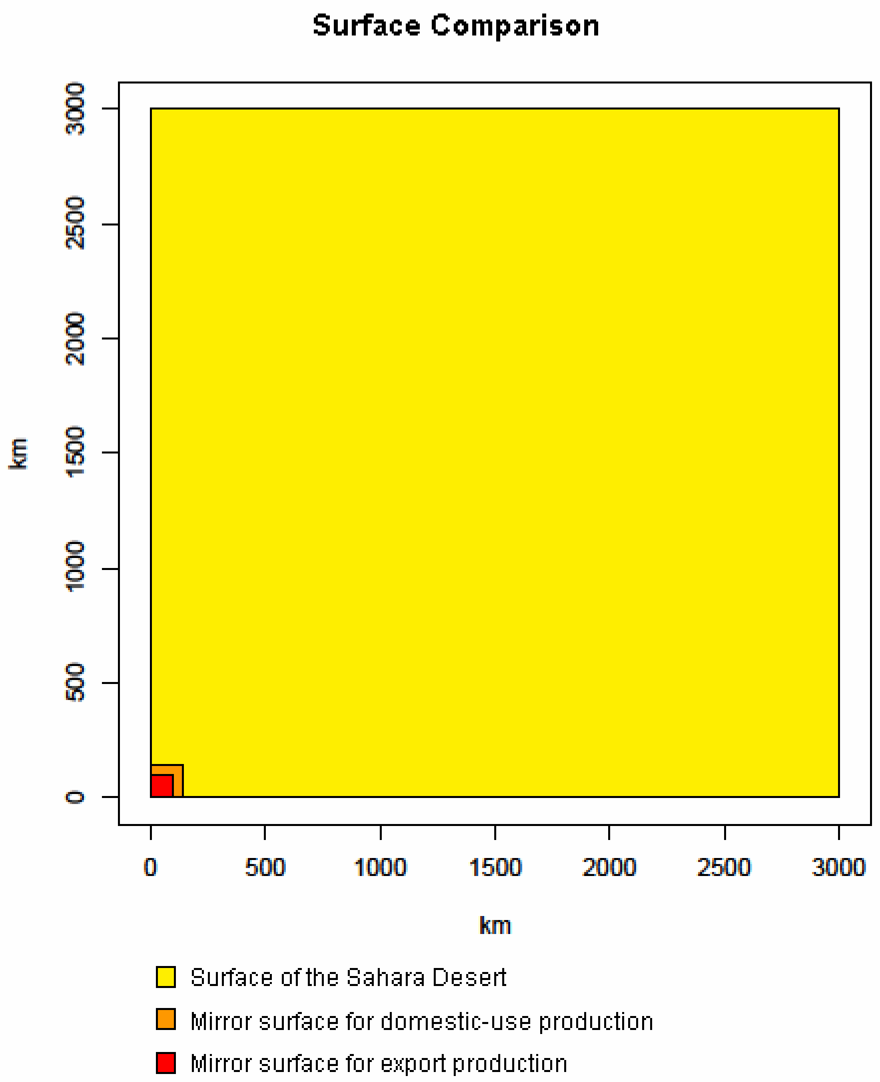
Stabilization policy costs



Note: Policy costs are reduced with respect to the case without the CSP-SG option

FONDAZIONE ENI ENRICO MATTEI

Is it feasible? - surface



Extreme case (no nuclear and no CCS):

Mirror surface needed for:

- Domestic production 10,500 Km^2
- Export 9,250 Km^2

- roughly the size of Slovenia (20,273 Km^2)

Space does not seem a major constraint

Is it feasible? – transmission lines

HVDC Cables for export (5GW)

	Bau	Stab	No Nuclear	No CCS	No Nuclear & CCS
2005	-	-	-	-	-
2010	-	-	-	-	-
2015	-	-	-	-	-
2020	-	-	-	-	-
2025	-	-	-	-	-
2030	-	-	-	-	-
2035	-	-	-	-	-
2040	-	-	-	-	0.3
2045	-	-	-	3	31
2050	-	-	7	22	68
2055	-	-	43	36	94
2060	-	17	75	47	113
2065	-	32	99	55	127
2070	-	44	118	62	138
2075	-	53	132	68	147
2080	-	61	145	73	156
2085	-	68	155	78	164
2090	-	73	164	82	170
2095	-	77	172	85	176
2100	-	81	178	88	181

FONDAZIONE ENI ENRICO MATTEI

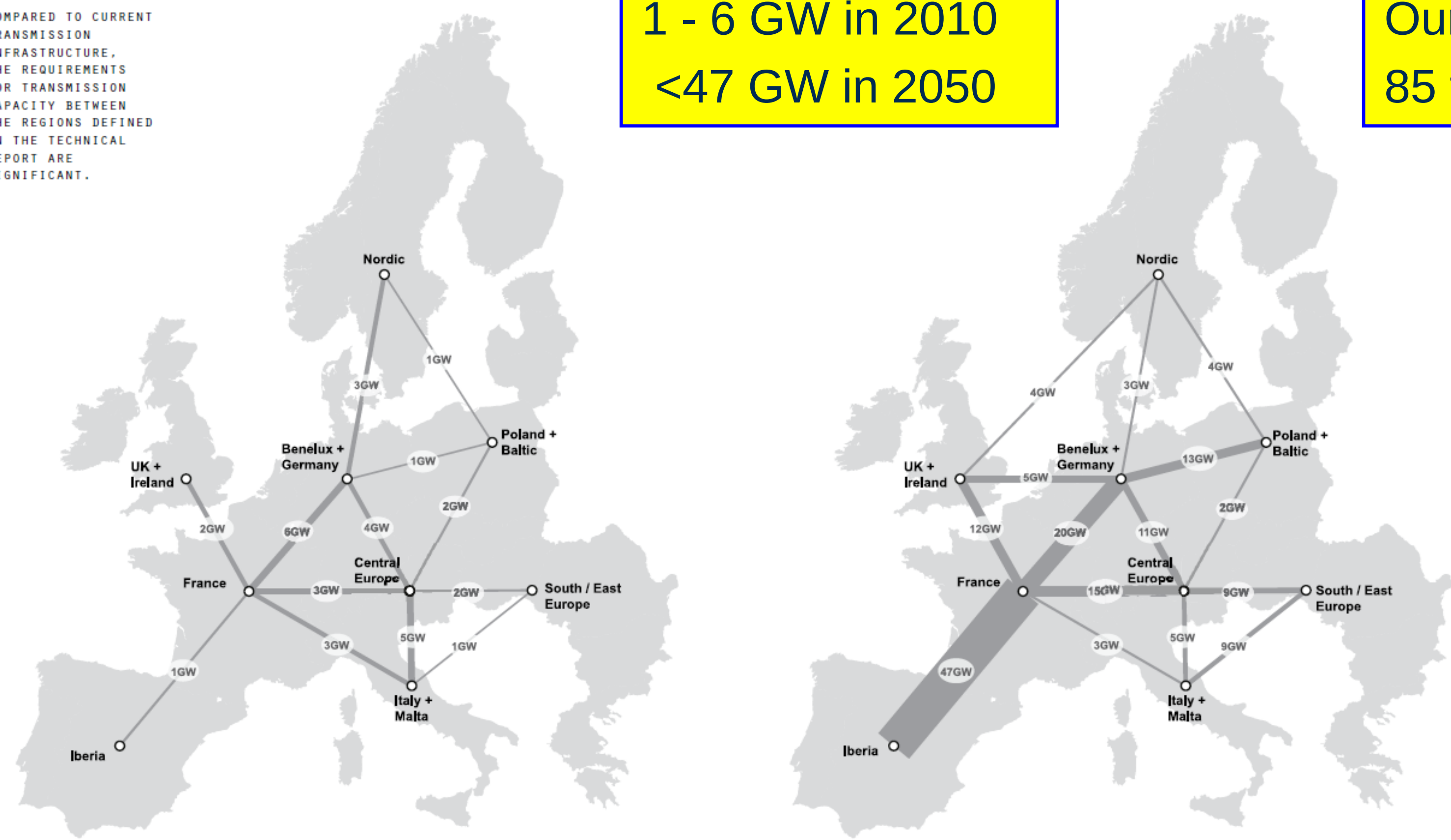
Is it feasible? – transmission lines

INTER-REGIONAL TRANSMISSION REQUIREMENTS

COMPARED TO CURRENT TRANSMISSION INFRASTRUCTURE, THE REQUIREMENTS FOR TRANSMISSION CAPACITY BETWEEN THE REGIONS DEFINED IN THE TECHNICAL REPORT ARE SIGNIFICANT.

1 - 6 GW in 2010
<47 GW in 2050

Our study, 2060:
85 to 564 GW



2010
Existing Capacity

2050
Total Transmission Requirements
Assuming 80% RES & 20% DR[1]

Very serious engineering and political challenge!

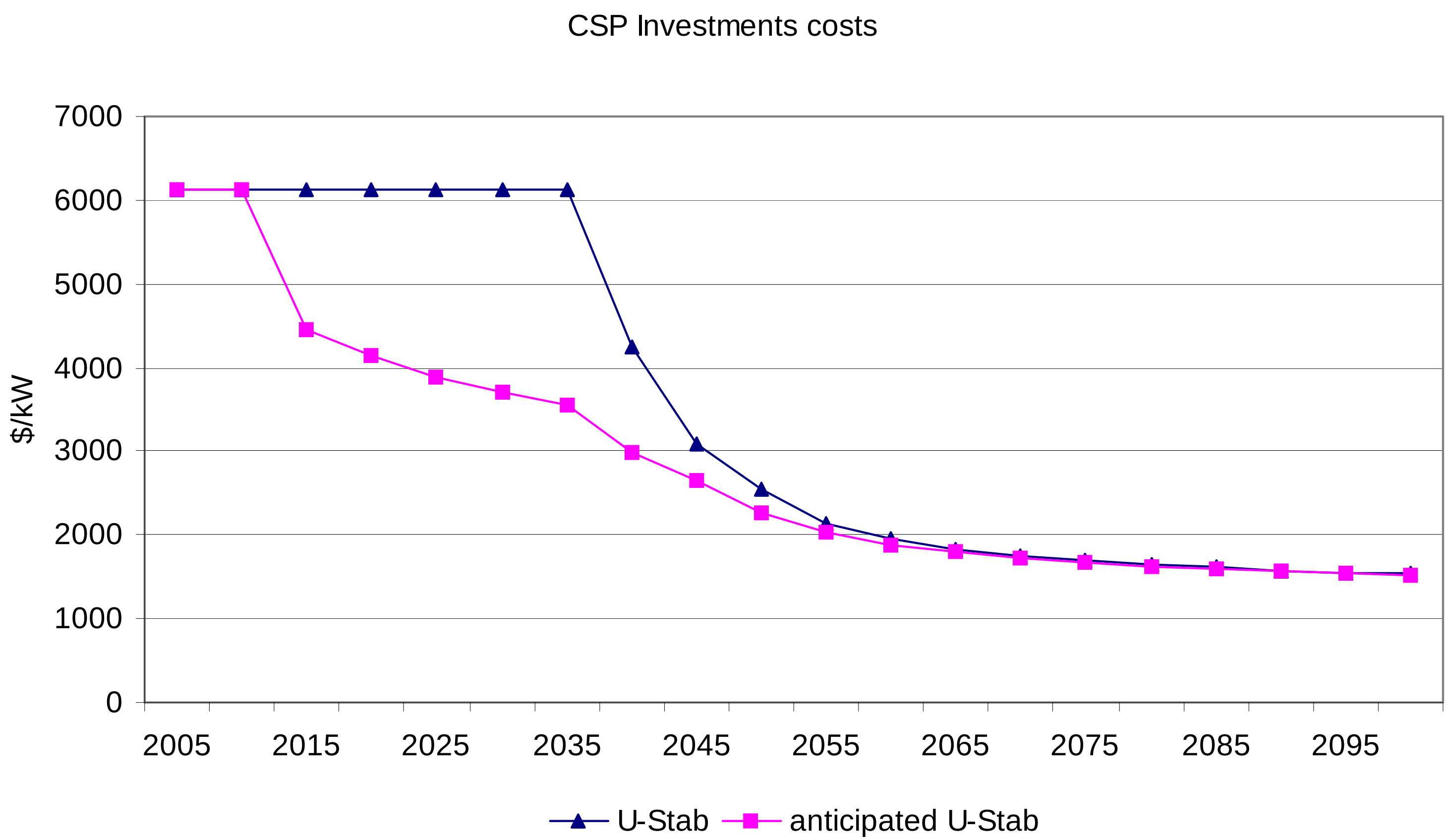
1GW
10GW
20GW

1 Demand response as used in this paper refers to changing a customer's electricity demand in response to dispatch instructions or price signals through communications technologies. In the Volume 1 analysis, it is assumed that any such changes retained the total energy consumed within the day, that is, moved or shifted demand rather than reduced total daily consumption
NOTE: Iberia-France link is challenging and maybe reduced by different solar/wind mix.
SOURCE: Roadmap 2050 Technical Analysis

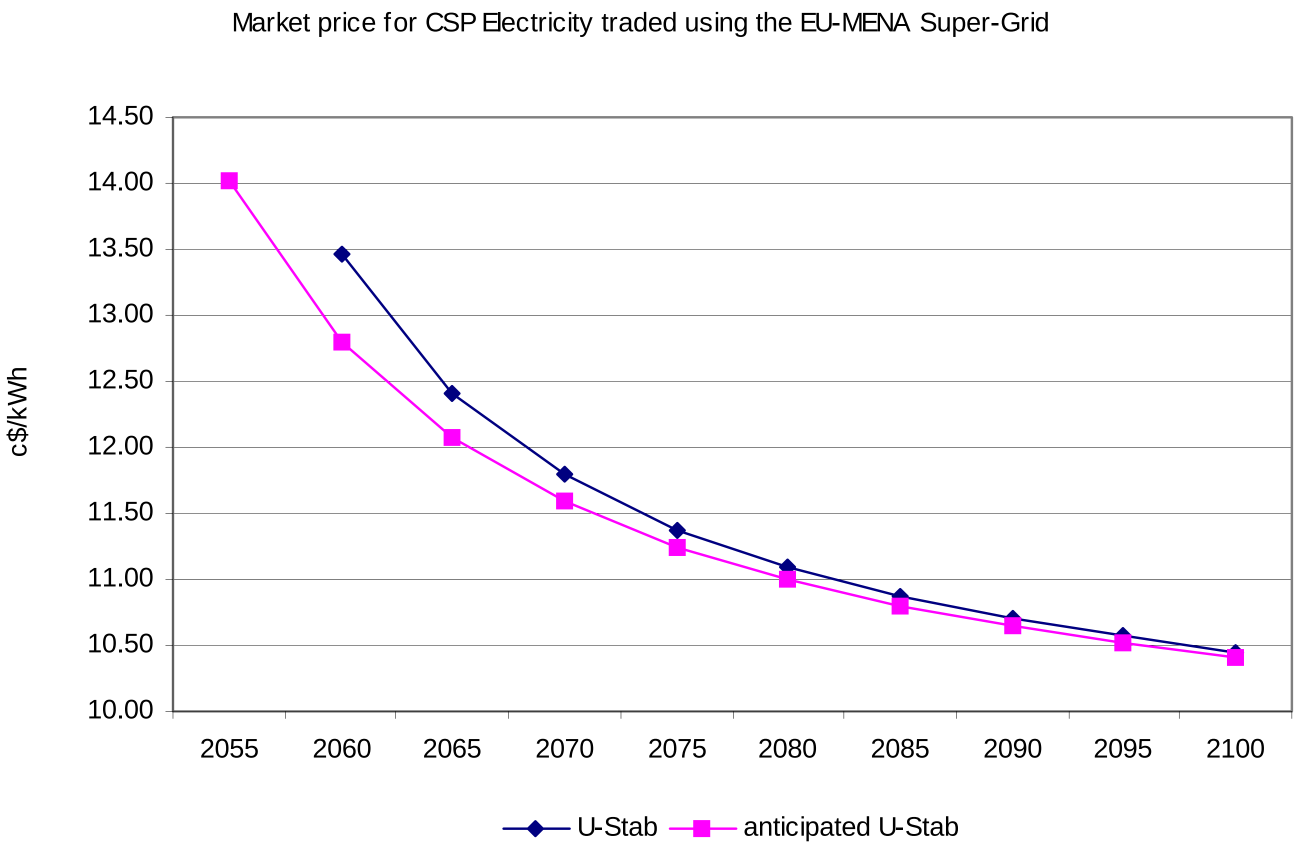
ECF - Roadmap 2050

Fondazione Eni Enrico Mattei

Anticipating investments in CSP (1)

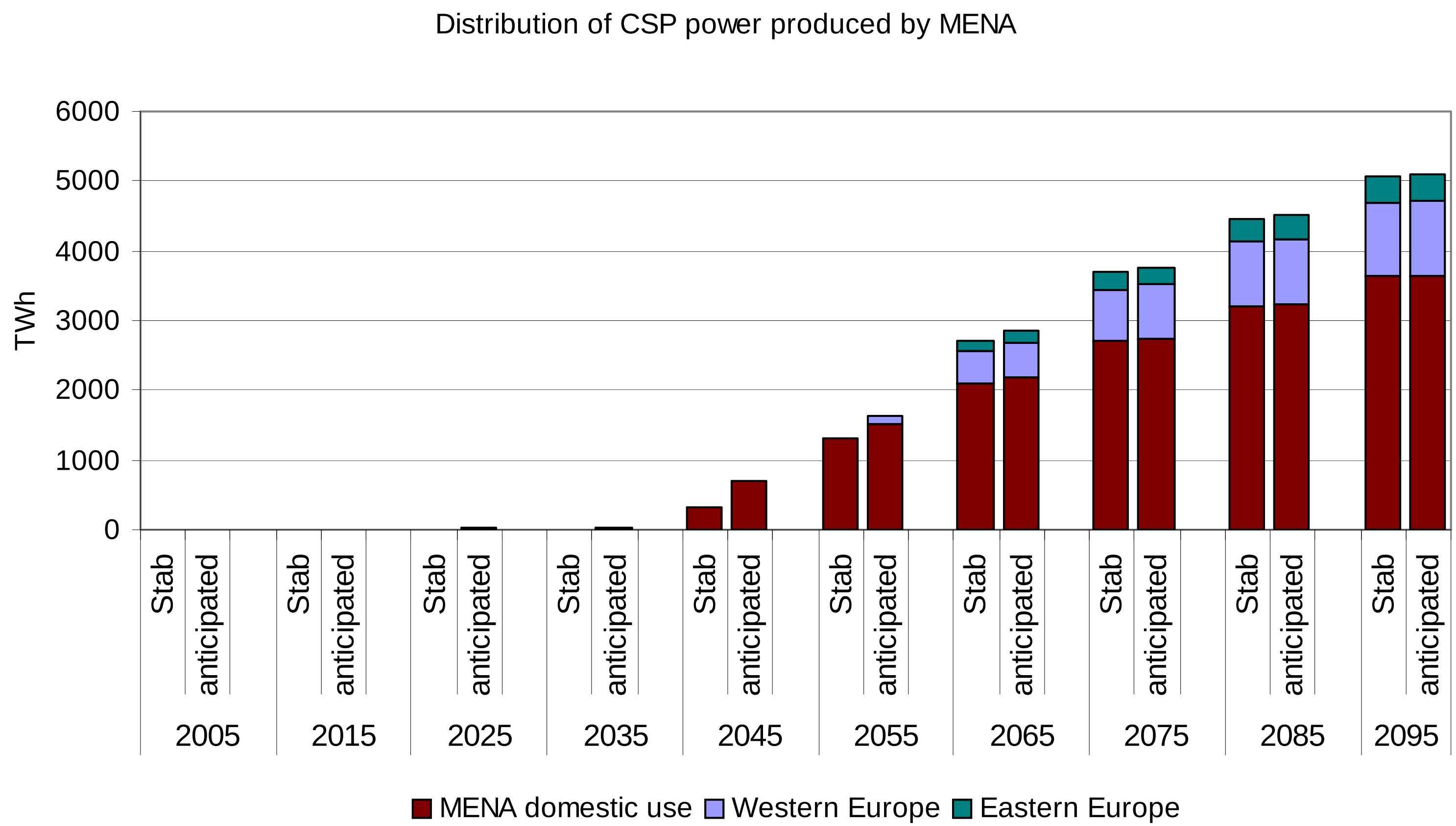


Anticipating investments in CSP (2)



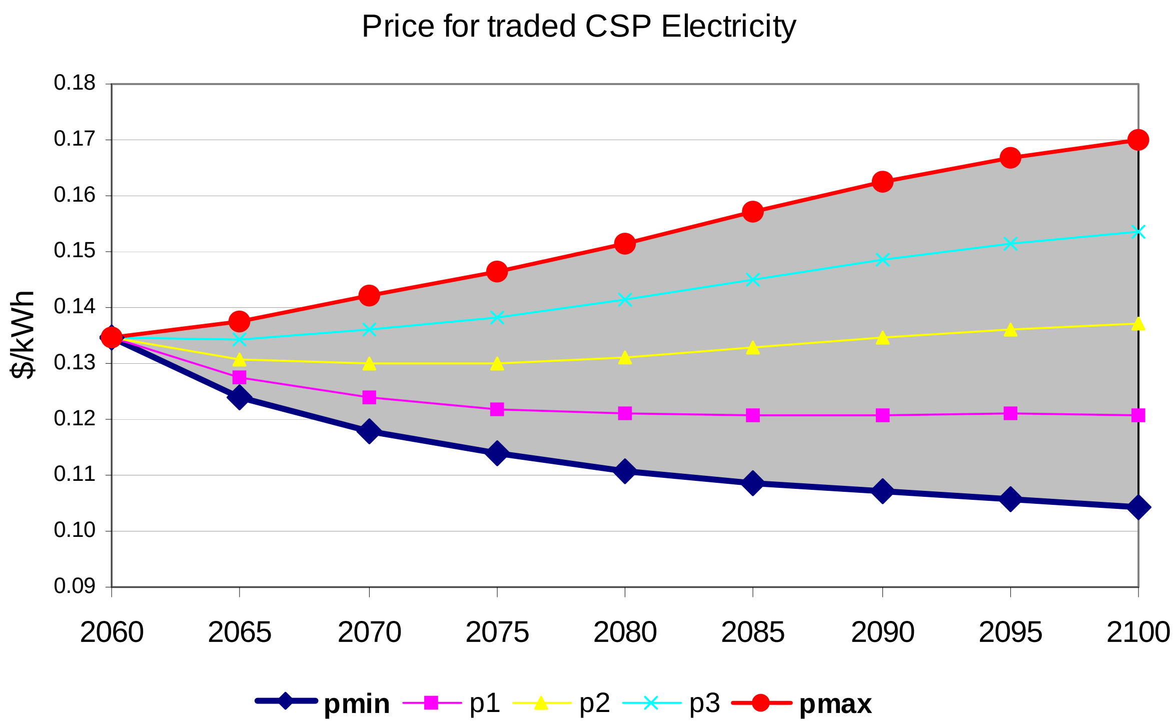
FONDAZIONE ENI ENRICO MATTEI

Anticipating investments in CSP (3)



Strategic behaviour (1)

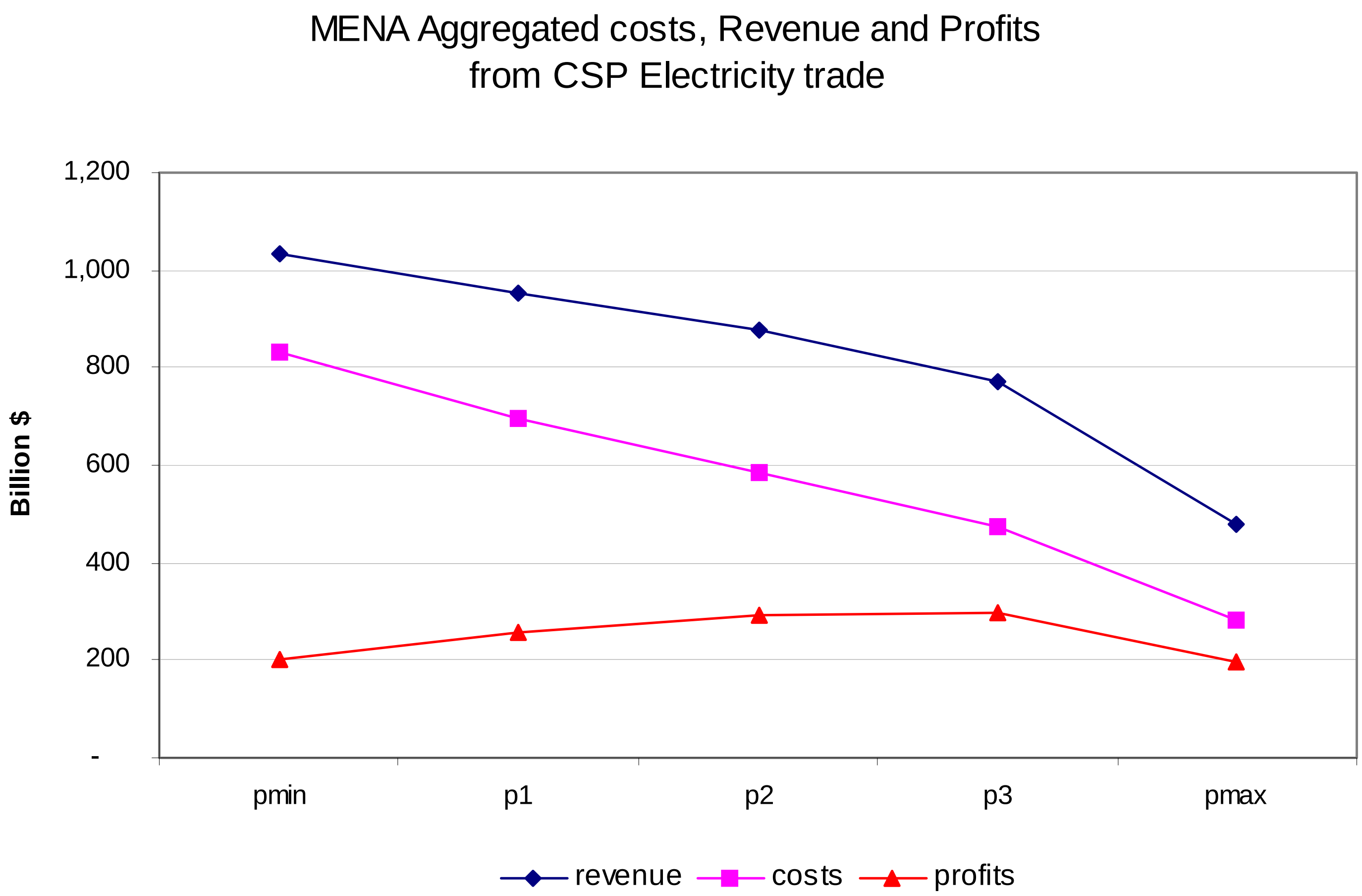
- Previous results based on the assumption of perfect competition
- Real market structure will allow strategic behaviour
- We have also evaluated:
  - Maximum price for which there is Demand
  - Minimum price for witch there is Supply (= Market price in competitive equilibrium)



FONDAZIONE ENI ENRICO MATTEI

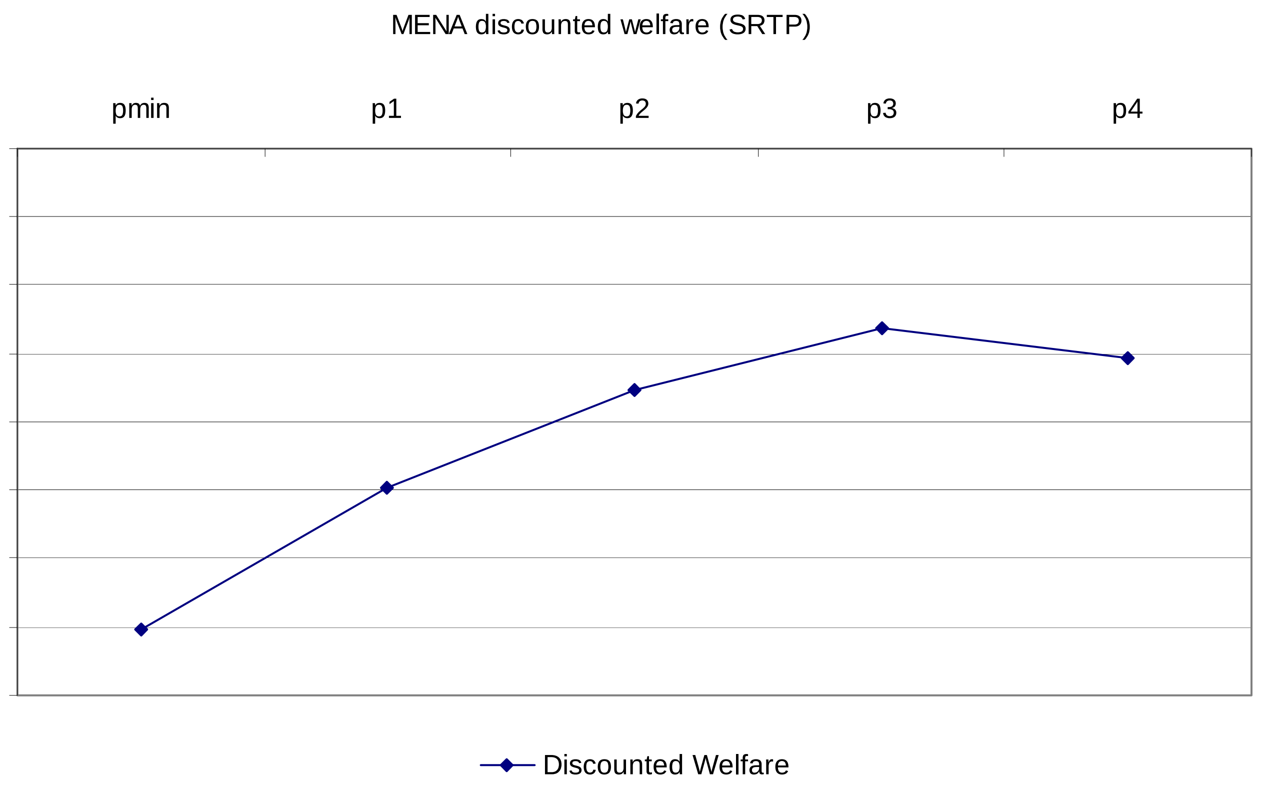
Strategic behaviour (2)

Indeed, analysing some intermediate vectors of prices we find that:



Strategic behaviour (3)

For what concerns welfare:



Conclusions

EU-MENA CSP-SG under a 550ppm-CO_2eq policy scenario with a global carbon market

- an **extensive use** will become optimal in the **second half of the century**;
- in the second part of the century,**CSP** will reach **very large shares** of electricity consumption;
- CSP-SG electricity in Europe and China substitutes **zero-carbon technologies** only when there are **penetration limits**;
- Domestic consumption by **MENA** is large and optimal also in the absence of climate policies;
- The **market price** for CSP trade between Europe and MENA is expected to start around 30c$/KWh and decrease over time to 10-11c$/KWh. Though, the price at which the CSP-SG electricity will be traded, will necessarily depend on **long-term international agreements**;
- the CSP-SG option also impacts the global GHG **emission permits market** reducing its size and decreasing the price of the emission permits
- the CSP-SG option allows **stabilization policy costs** to be reduced
- A coordinated **anticipation of investments** in CSP reduces investments costs earlier and allows countries to have higher levels of consumption, in aggregate terms.

FONDAZIONE ENI ENRICO MATTEI

Future Steps

Future work will focus on:

- Linking CSP electricity trade with Oil trade,
- Introducing the spatial dimension in order to take into account geographic variability,
- Extend the analysis to other innovations of the electric power grid.

Thank You

elena.ricci@feem.it