Optimal location of wind power –

The social cost of uniform versus non-uniform feed-in tariffs.

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Background

- Renewable targets – subsidizing new renewable production capacities. (Feed in –tariffs/certificate systems).
- Subsidies often differentiated across sources, but not across locations.
- Locations matters for the system cost (transmission costs).
- Some of these cost are not faced by the producers.
- Old problem – but increases with increasing renewable energy capacities, located far from the consumers.

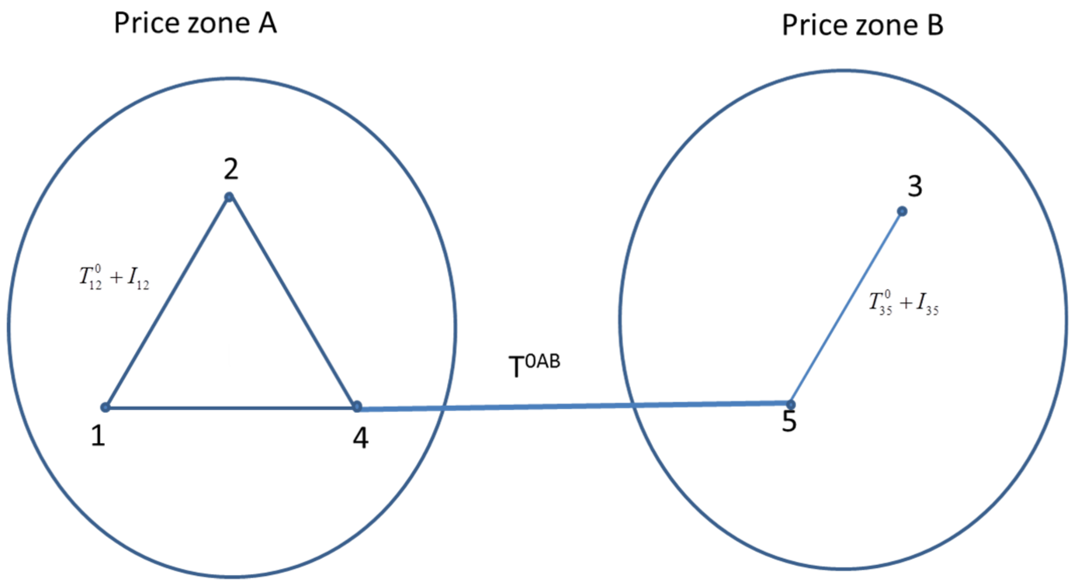
Outline of the paper

- Analytical model
  - Capture the main characteristics of a zonal electricity market (as the Norwegian system):
    - Derive the conditions for an optimal geographical distribution of new renewable energy capacities.
    - Design of optimal (non-uniform) feed-in tariffs.
- Numerical Model
  - TIMES
    - Numerical illustration of the social cost of uniform feed-in tariffs compared to optimal feed-in tariffs
      (for the Norwegian energy system)
- Laws and regulations

Analytical model

- Energy Act: Grid companies are required to connect to new electricity production and to carry out the necessary investments in their grid.
- “Loop flow” problems - power transfer from one production node to a consumption node can affect the transmission capacities of third parties (Alternate current grid - electricity follows the path of least resistance).
- Shallow connection charges (versus deep connection charges). Producer do not take into account the cost of accommodating additional generation.

Electric power network



Production nodes: 1, 2 and 3. (q_1, q_2 and q_3).
Consumption nodes: 4 and 5. (q^{CA} and q^{CB}).
T = Transmission capacities.
All variables measured in MW (capacities).
(fixed conversion factors from capacity to energy).
Prize zone A; loop flow (AC transmission).

The objective function is

$$\text{Max } W = U^{A}(q^{CA}) + U^{B}(q^{CB}) - \left[c_1^{A}(q_1) + c_3^{A}(q_3) + c_3^{B}(q_3) + k(I_{12}) + d(I_{35})\right]$$

Subject to

Renewable target: $q^{R} = q_1 + q_2 + q_3$

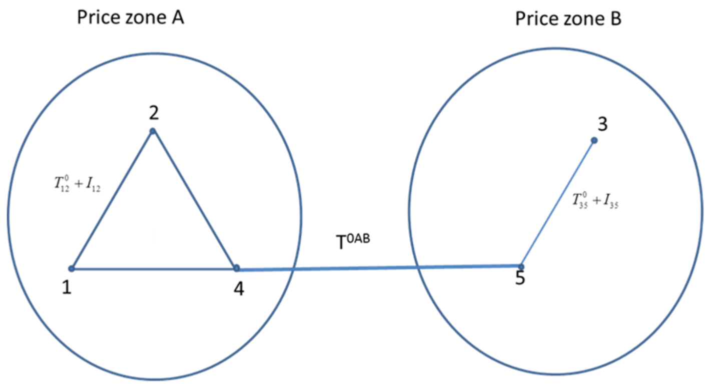
Transmission constraints:

$$\frac{1}{3}q_1 - \frac{1}{3}q_2 \le T_{12}^{0} + I_{12}$$

$$q_3 \le T_{35}^{0} + I_{35}.$$

$$q^{CA} - (q_1 + q_2) \le T_{AB}^{0}$$

$$q^{CA} + q^{CB} = q_1 + q_2 + q_3$$



Non-binding transmission constraints.

$$U^{A\prime} = U^{B\prime}$$

$$c_1^{A\prime} = c_2^{A\prime} = c_3^{B\prime}$$

$$U^{j\prime} = c_i^{A\prime} - \lambda_1 = c_3^{B\prime} - \lambda_1 \quad i = 1,2 \quad j = A, B$$

The optimal distribution of consumption is such that the marginal benefit of consumption is equalized across prize zones

The optimal distribution of renewable production capacities is such that the marginal cost of production should be equalized across all production nodes.

Due to the binding renewable constraint, marginal cost of production exceeds the marginal benefit from consumption.

Binding transmission constraints

$$k' = \frac{3}{2}\left[c_2^{A'} - c_1^{A'}\right]$$

$$\lambda_4 = U^{A'} - U^{B'}$$

$$\lambda_1 = c_3^{B'} - U^{B'} + d' = c_1^{A'} - U^{A'} + \frac{1}{3}k' = c_2^{A'} - U^{A'} - \frac{1}{3}k'$$

For binding transmission constraints, the marginal cost of production capacity will differ within price zones ($c_1^{A'} \neq c_2^{A'}$**)** and across price zones ($c_3^{B'} \neq c_i^{A'}$**).**

Feed-in tariffs , F_i

Profit maximizing behavior leads to the following first order conditions:

$$c_1^{A\prime}(q_1) = p^A + F_1$$
$$c_2^{A\prime}(q_2) = p^A + F_2$$
$$c^{B\prime}(q_3) = p^B + F_3$$

$$U_1^{A\prime}(q^{CA}) = p^A$$
$$U_1^{B\prime}(q^{CB}) = p^B$$

Optimal tariffs in the case of non-binding transmission constraints: $F_i = \lambda_1^* \quad i = 1, 2, 3$

Optimal tariffs in the case of binding transmission constraints:

$$F_1^{**} = \lambda_1^{**} - \frac{1}{3} k'(I_{12}^{**})$$
$$F_2^{**} = \lambda_1^{**} + \frac{1}{3} k'(I_{12}^{**})$$
$$F_3^{**} = \lambda_1^{**} - d'(I_{35}^{**})$$

With binding transmission constraint, and shallow connection charges, the feed-in tariffs should in general differ across production nodes.

What is the social cost of uniform versus optimal non-uniform feed-in tariffs?

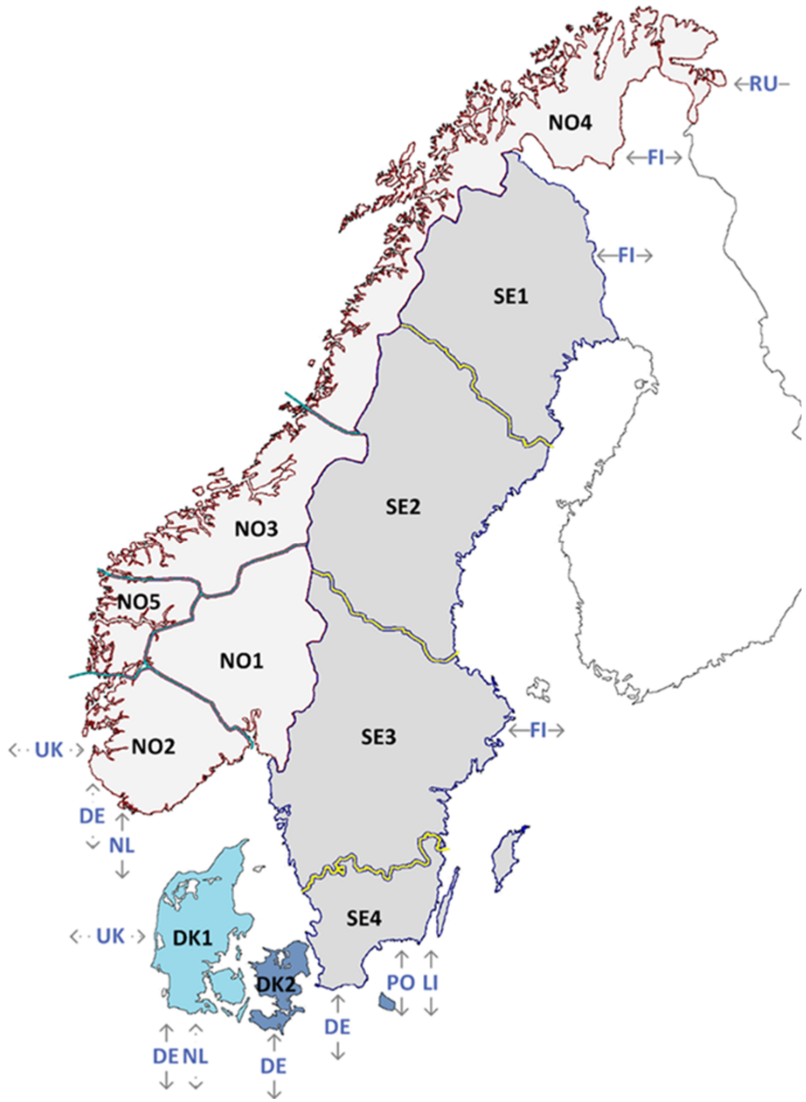
Numerical illustration

Modelling framework

- An energy system model (TIMES-Norway) has been used to analyse the optimal location of renewable power plants in Norway
- TIMES-Norway gives a detailed description of the *entire energy system* including:
  - Resources
  - Energy production technologies
  - Energy carriers
  - Demand devices
  - Sectorial demand for energy services
- The model assumes perfect competition and perfect foresight and is demand driven
- The TIMES model aims to supply energy services at *minimum global cost* by making
  - Equipment decisions
  - Operating decisions
  - Primary energy supply and energy trade decisions

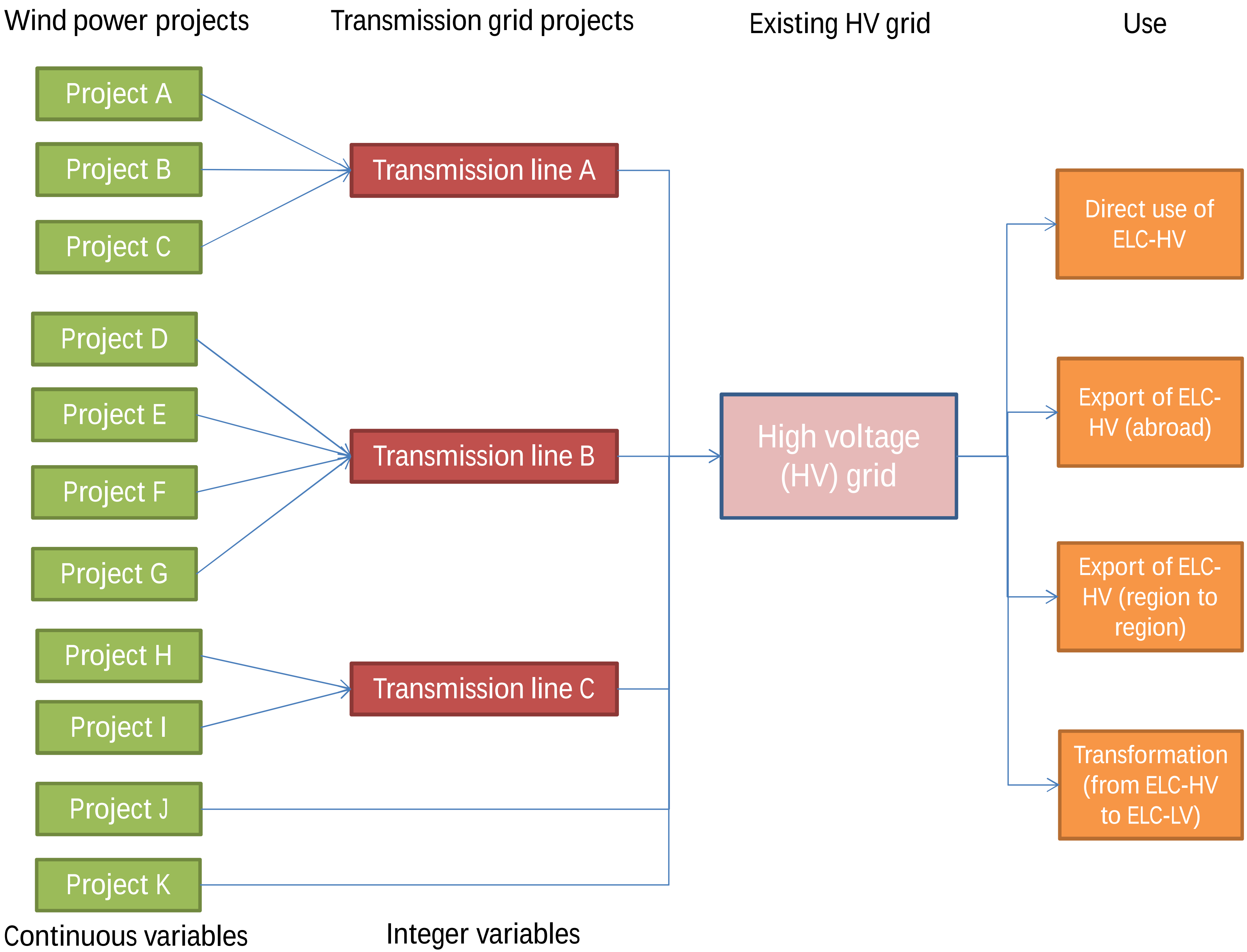
Energy system model

- A modified version of TIMES-Norway is used to analyze the optimal location of new wind power plants based on various transmission grid assumptions
- Base year: 2010
- Model horizon: 2010 – 2050
  - Divided into periods of five years
  - Each period: 12 two-hour steps for a representative day of four different seasons
- The model covers Norway, Sweden and Denmark
  - Exchange of electricity between regions and neighboring countries



Transmission grid modelling

- In order to model certain investment decisions, the linearity property of the TIMES model becomes a drawback
  - E.g. whether or not to build a new transmission grid connection
  - The TIMES linear programming (LP) model is therefore transformed into a *Mixed Integer Linear Model (MILP)* to accommodate discrete decisions
  - This ensures that investments in a certain technology, *k*, is equal to one of a finite number *(N)* of pre-determined sizes
- For several of the price areas in the Nordic spot market, the existing transmission grid has a limited capacity for new power projects
  - Extensive plans for expanding and strengthening of the grid exist
  - These projects will depend on various investment decisions related to renewable power technologies
  - Several of the potential new power projects in Norway will require investments in the transmission grid


Wind power projects
Transmission grid projects
Existing HV grid
Use
Project A
Project B
Project C
Project D
Project E
Project F
Project G
Project H
Project I
Project J
Project K
Transmission line A
Transmission line B
Transmission line C
High voltage (HV) grid
Direct use of ELC-HV
Export of ELC-HV (abroad)
Export of ELC-HV (region to region)
Transformation (from ELC-HV to ELC-LV)
Continuous variables
Integer variables

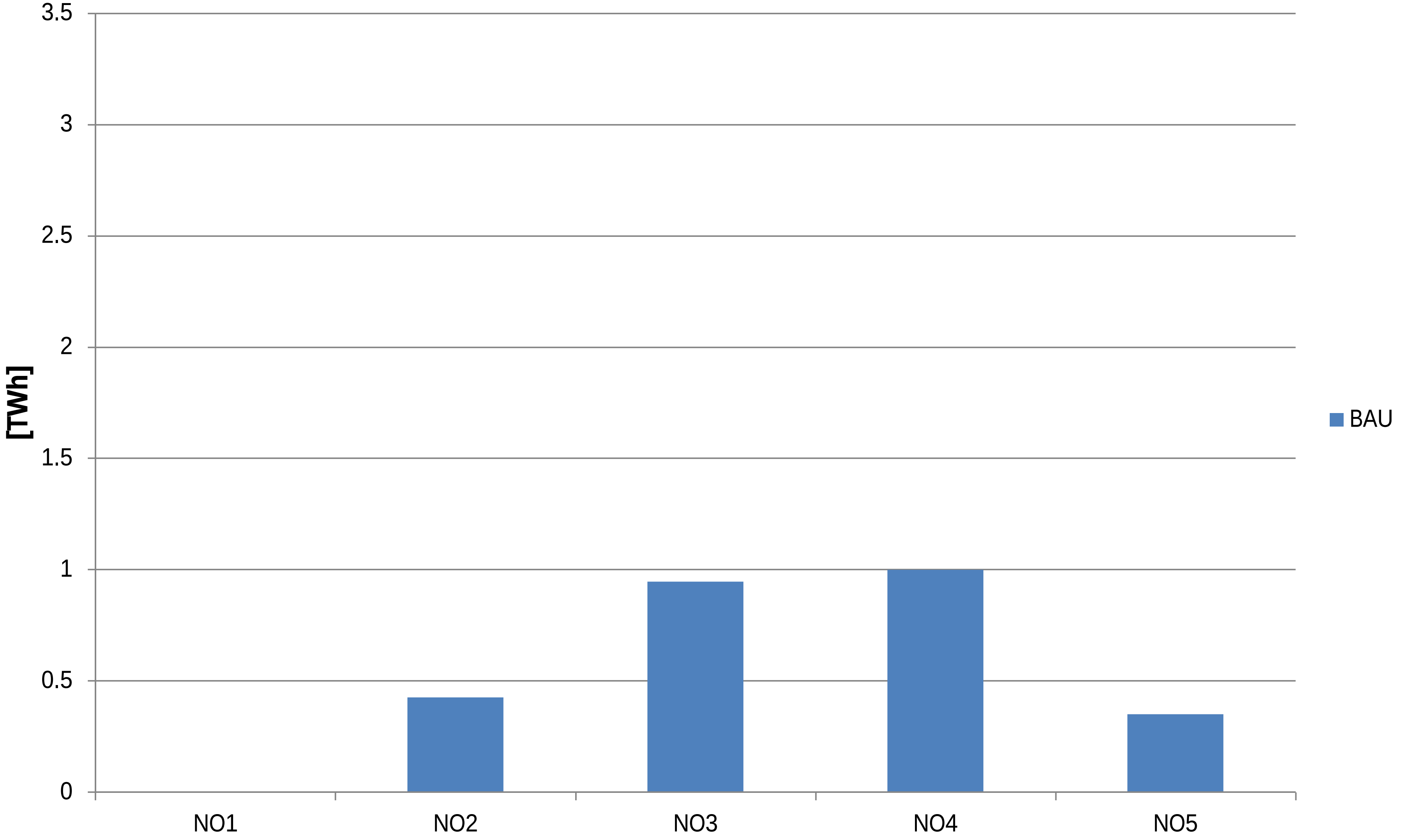
Scenario assumptions

- Energy end use demand:
  - Supplied exogenously to the model
  - Based on on the development of drivers and indicators of each demand sector
  - CenSES energy demand projections towards 2050 – Reference path
- The analyses include all active national measures of today
- The energy taxes are kept constant at the 2014 level until 2050
- Energy prices for imported energy carriers are based on (Energinet.dk, 2015)
  - The prices of electricity import/export, to and from Scandinavia, are given exogenously

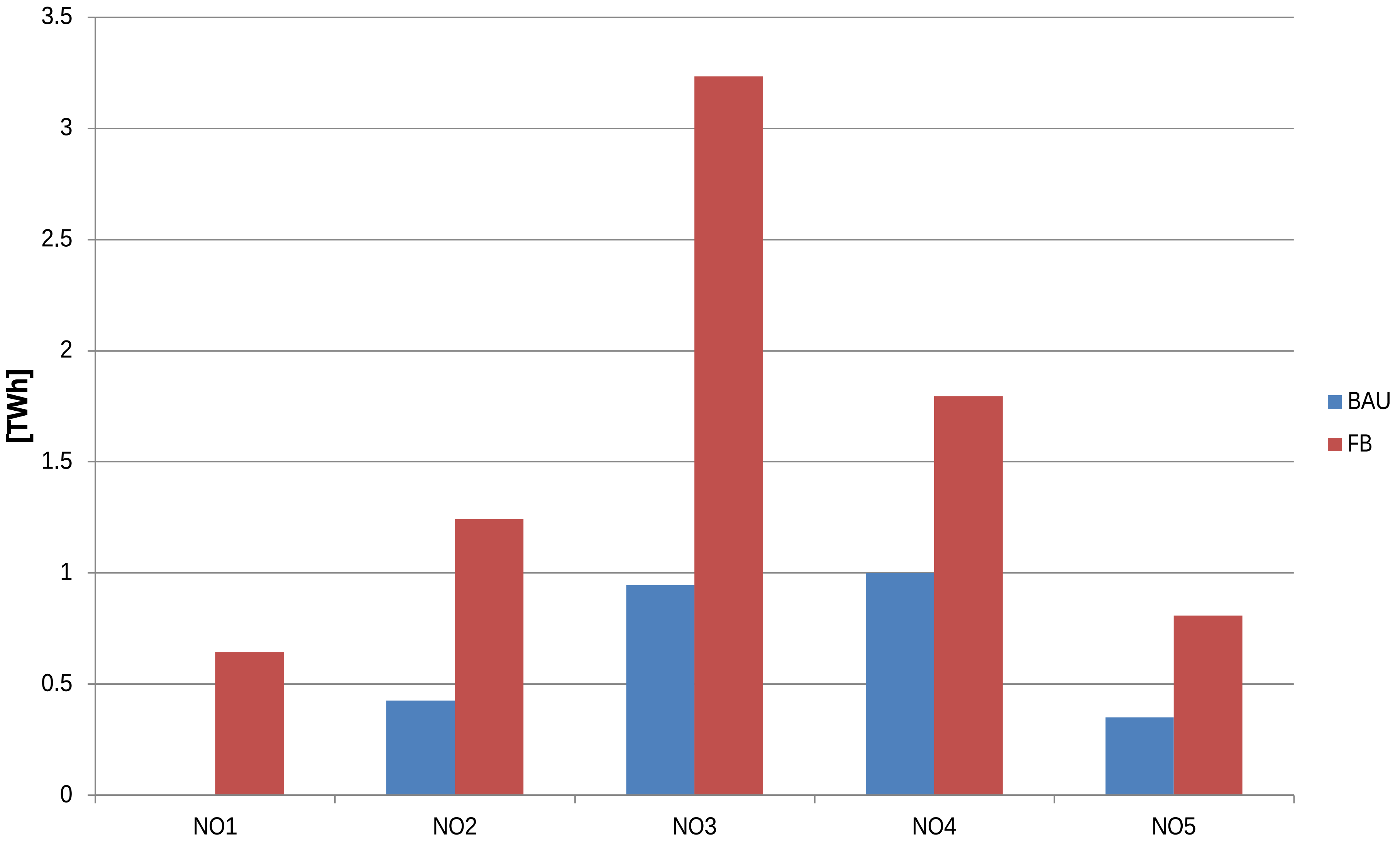
Scenario description

- Business as usual (BAU)
  - Includes all current national policies
  - Used to illustrate the effects of the policies analysed in the other scenarios
- First best (FB)
  - We added a restriction requiring 5 TWh of new wind power production in Norway by 2020
  - Necessary investments in the transmission grid are included in the analysis
  - The TIMES model will find the optimal distribution of wind power across price areas, taking into account the costs of transmission upgrades
- Profit max (PM)
  - The costs of necessary transmission upgrades are ignored by the power producers
  - The TIMES model will then identify the optimal distribution of wind power across the price areas

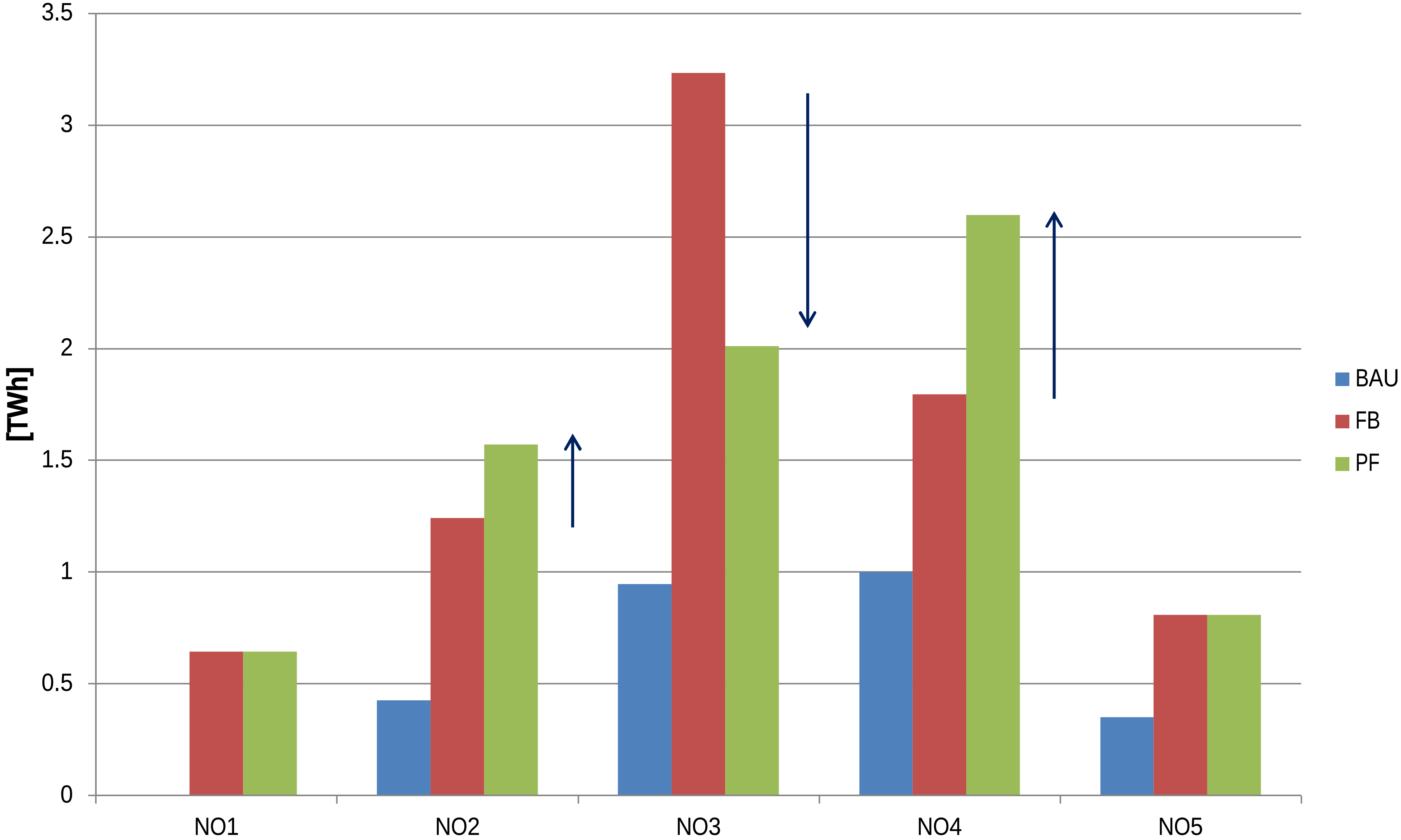
Wind power production



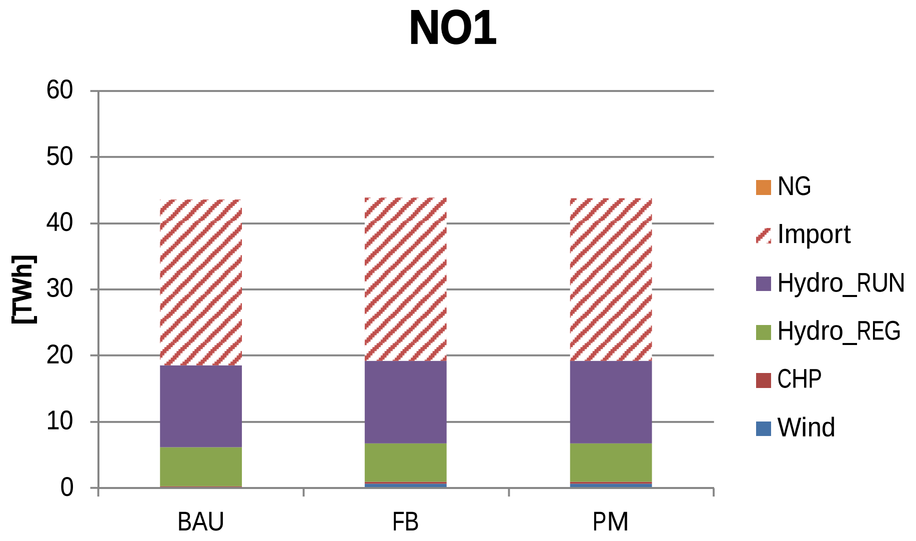
Wind power production

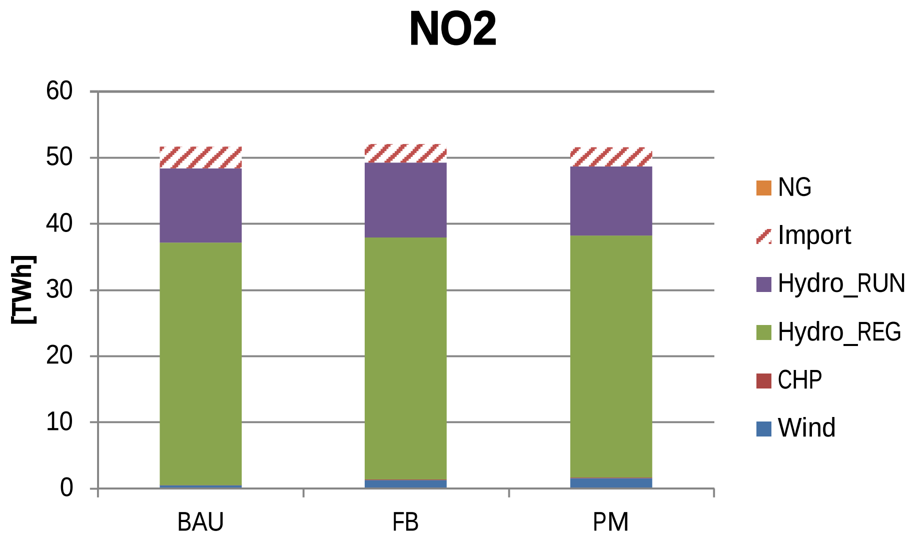


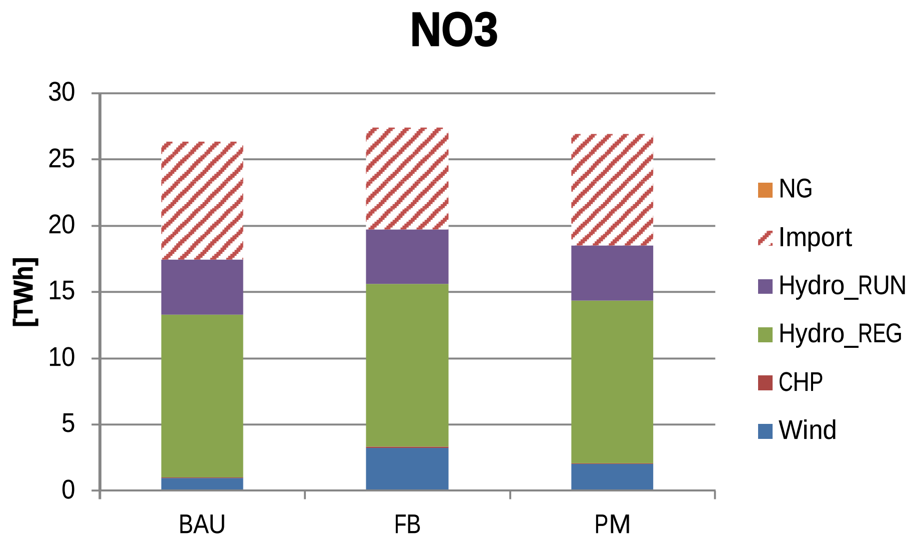
Wind power production

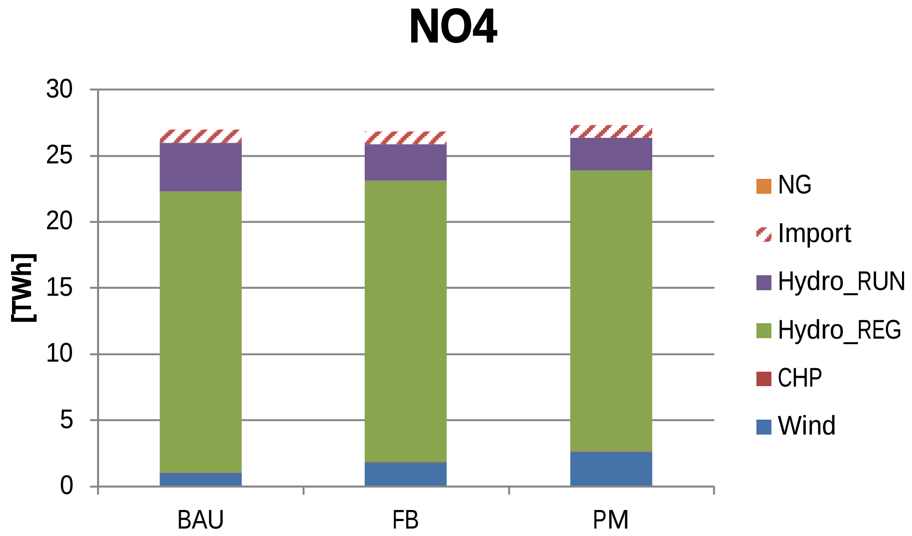


Power production + imports

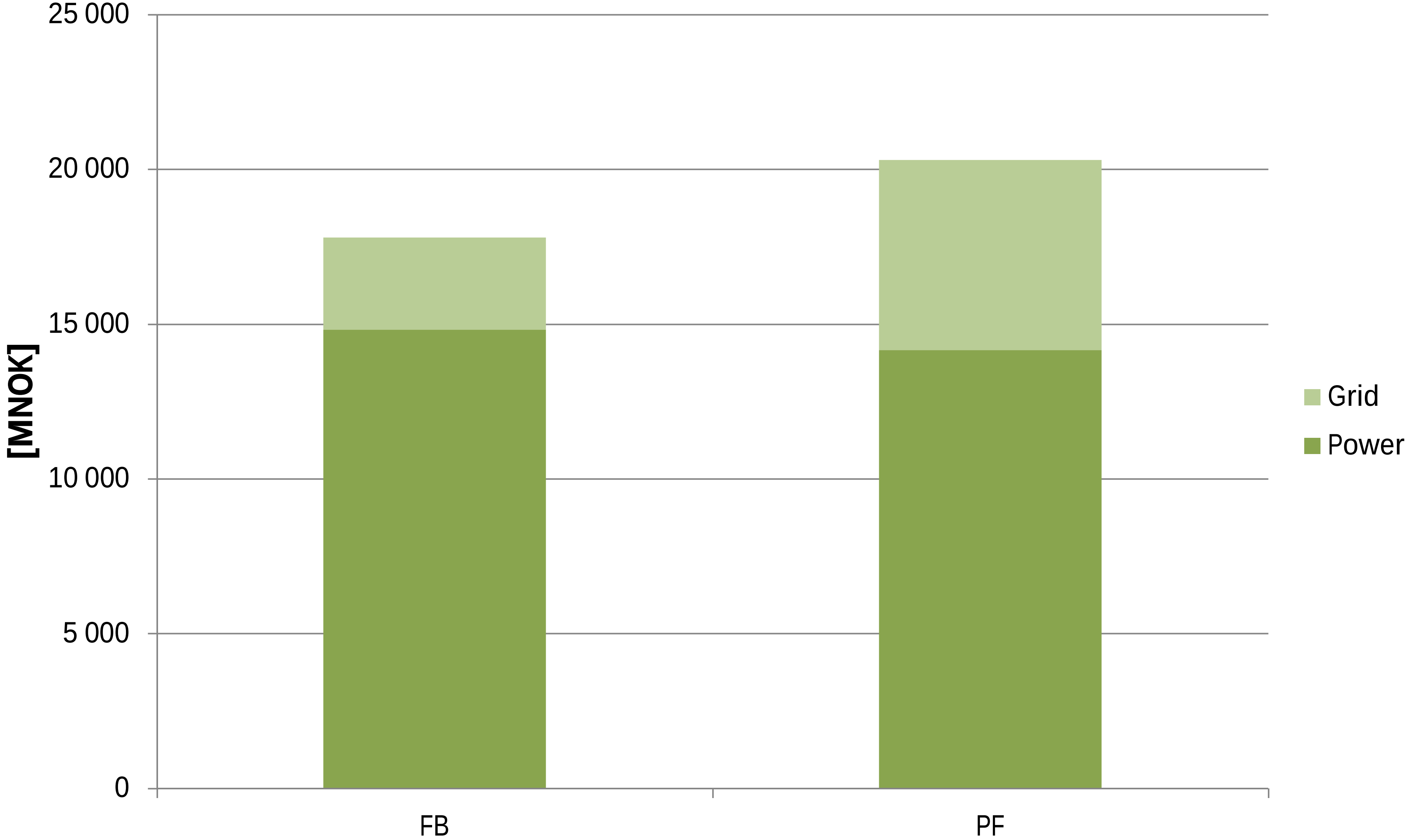




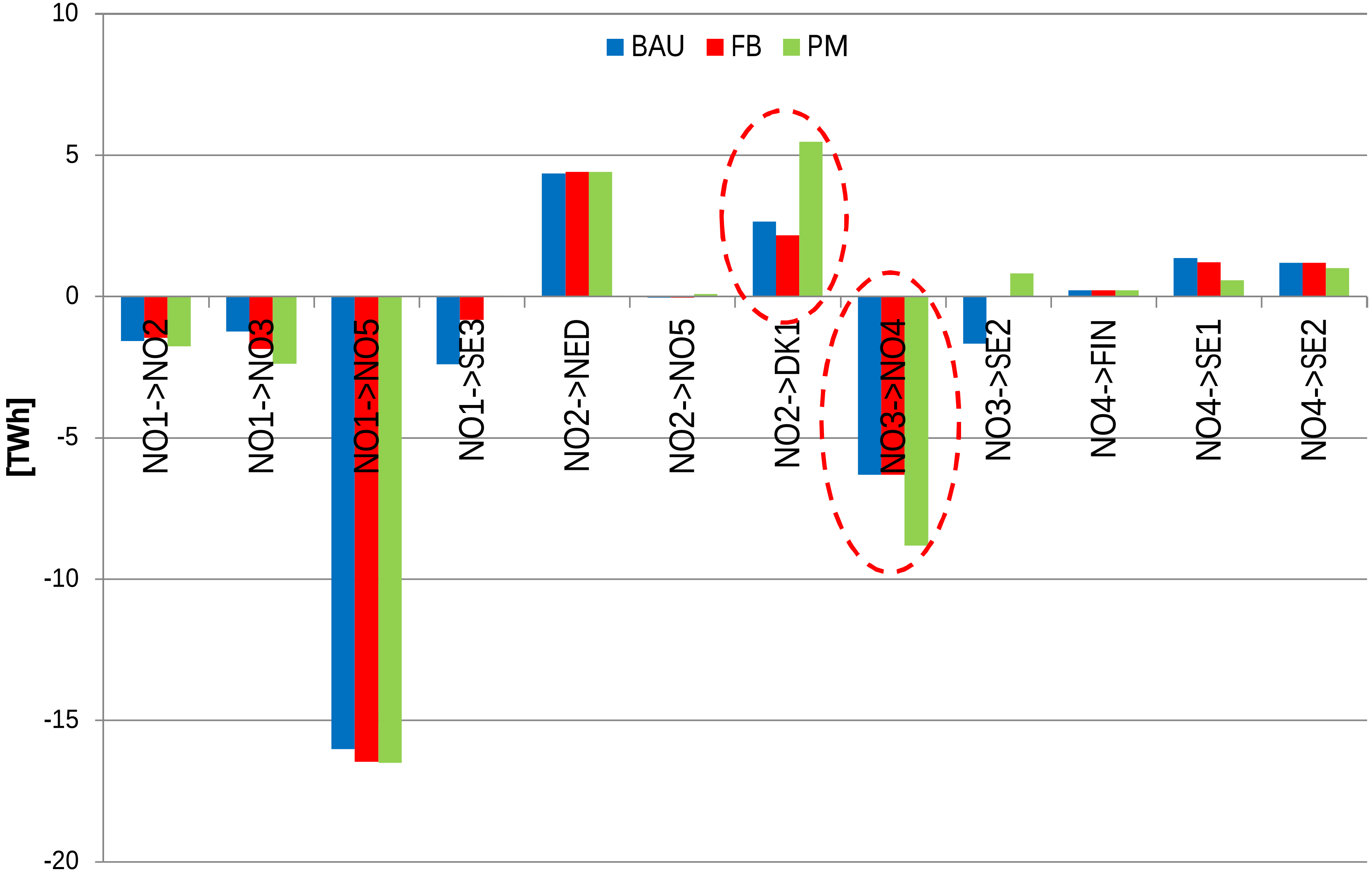




Investment costs: Wind and grid

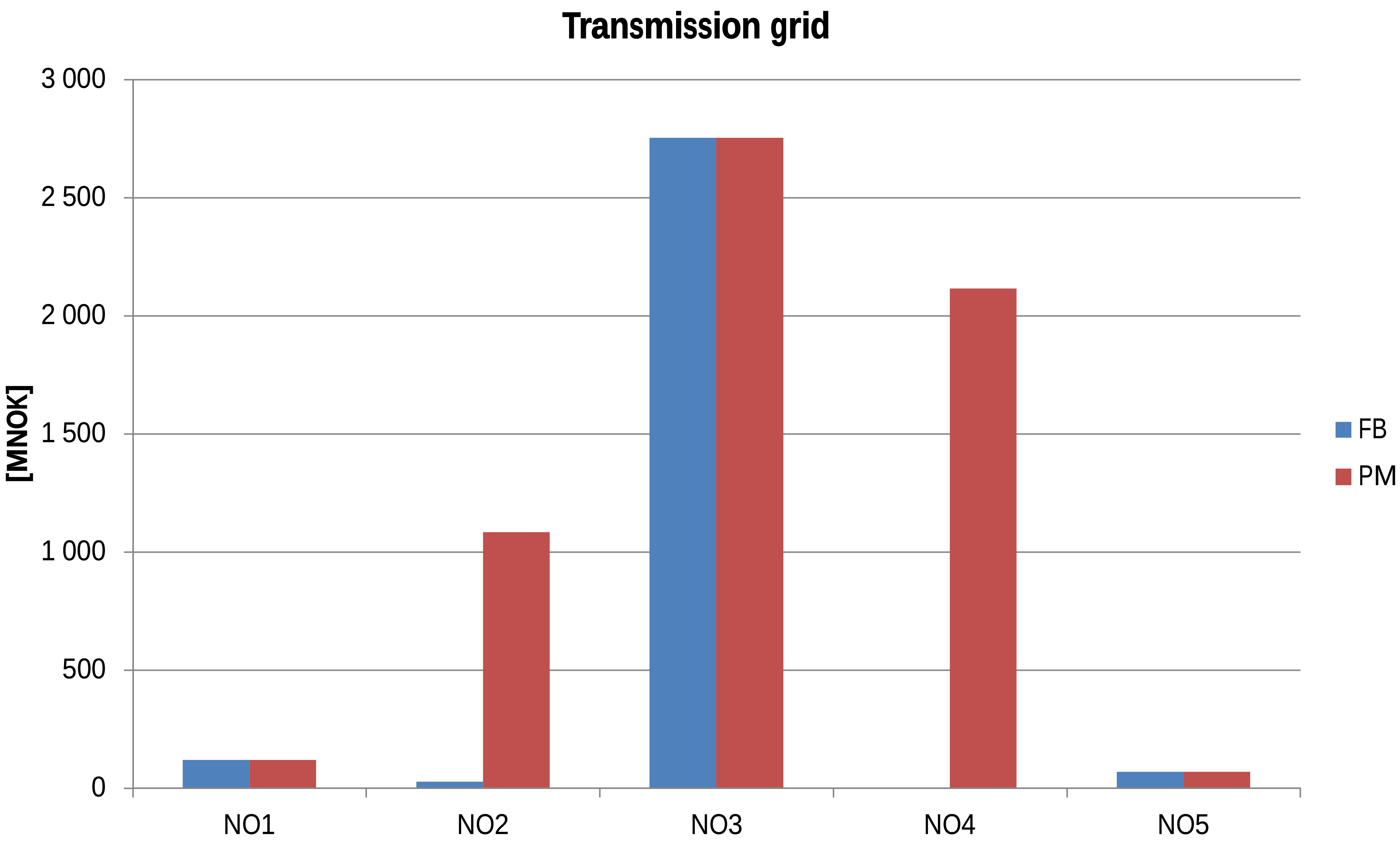


Net export



BAU
FB
PM
10
5
0
-5
-10
-15
-20
[TWh]
NO1->NO2
NO1->NO3
NO1->NO5
NO1->SE3
NO2->NED
NO2->NO5
NO2->DK1
NO3->NO4
NO3->SE2
NO4->FIN
NO4->SE1
NO4->SE2

Investment cost per region



Concluding remarks

- Profit max (PM)
  - The production increase is largest in NO4 (northernmost price area)
  - This is largely due to the high capacity factors (i.e. better wind conditions) experienced in this area
  - Increased net export
  - Increased trade between NO3 and NO4 (from NO4 to NO3)
- First best (FB)
  - The production increase is now largest in NO3 (middle of Norway)
  - PM will require a lot of grid investments in NO4 to transport the electricity out of the region
  - It is therefore more cost effective to take both power and grid investments in NO3


Thank you