FONDAZIONE ENI
ENRICO MATTEI

NOTA DI LAVORO

37.2017

The Effect of Increased Transmission and Storage in an Interconnected Europe: an Application to France and Ireland

Valeria Di Cosmo, FEEM
Sean Collins, MaREI Centre,
Environmental Research Institute,
University College Cork
Paul Deane, MaREI Centre,
Environmental Research Institute,
University College Cork

Energy Scenarios and Policy
Series Editor: Manfred Hafner

The Effect of Increased Transmission and Storage in an Interconnected Europe: an Application to France and Ireland

By Valeria Di Cosmo, FEEM
Sean Collins, MaREI Centre, Environmental Research Institute, University College Cork
Paul Deane, MaREI Centre, Environmental Research Institute, University College Cork

Summary

A longstanding goal of the European Union (EU) is to promote efficient trading between price zones via electricity interconnection to achieve a single electricity market between the EU countries. This paper uses a power system model (PLEXOS-EU) to simulate one vision of the 2030 EU electricity market based on European Commission studies to determine the effects of a new interconnector between France and the Single Electricity Market of Ireland and Northern Ireland (SEM). We use the same tool to understand the effects of investment in storage, and the effects of the interaction between storage and additional interconnection. Our results show that both investments in interconnection and storage reduce wholesale electricity prices in France and Ireland as well as reduce net revenues of thermal generators in most scenarios in both countries. However, France is only marginally affected by the new interconnector. Renewable generators see a modest increase in net revenues. The project has the potential for a positive impact on welfare in Ireland if costs are shared between countries and remain below 45 million €/year for the scenarios examined. The owners of the new interconnector between France and SEM see increased net revenues in the scenarios without storage. When storage is included in the system, the new interconnector becomes less profitable.

Keywords: Interconnection, Renewable Generation, Storage

JEL Classification: Q4, Q48

Address for correspondence:
Valeria Di Cosmo
Fondazione Eni Enrico Mattei
Corso Magenta, 63
20123 Milan
Italy
E-mail: valeria.dicosmo@feem.it

The effect of increased transmission and storage in an interconnected Europe: an application to France and Ireland

Valeria Di Cosmo*.[1], Sean Collins[2], and Paul Deane[2]

[1]FEEM, Milano.
[2]MaREI Centre,Environmental Research Institute, University College Cork

Abstract

A longstanding goal of the European Union (EU) is to promote efficient trading between price zones via electricity interconnection to achieve a single electricity market between the EU countries. This paper uses a power system model (PLEXOS-EU) to simulate one vision of the 2030 EU electricity market based on European Commission studies to determine the effects of a new interconnector between France and the Single Electricity Market of Ireland and Northern Ireland (SEM). We use the same tool to understand the effects of investment in storage, and the effects of the interaction between storage and additional interconnection. Our results show that both investments in interconnection and storage reduce wholesale electricity prices in France and Ireland as well as reduce net revenues of thermal generators in most scenarios in both countries. However, France is only marginally affected by the new interconnector. Renewable generators see a modest increase in net revenues. The project has the potential for a positive impact on welfare in Ireland if costs are shared between countries and remain below 45 million €/year for the scenarios examined. The owners of the new interconnector between France and SEM see increased net revenues in the scenarios without storage. When storage is included in the system, the new interconnector becomes less profitable.

Keywords: interconnection; renewable generation; storage
JEL Classification: Q4; Q48

---

*Corresponding author. E-mail: valeria.dicosmo@feem.it, FEEM Corso Magenta 63, Milano, Italy

1 Introduction

A longstanding goal of the European Union (EU) has been to create a single electricity market (European Single Electricity Market-ESEM). The ESEM has been in place since 2014, even if some Member States were allowed to delay joining the Single Market until 2018.[1] The framework for the EU internal market is contained in the Third Energy Package, which came into effect in March 2011, along with a detailed set of directives designed to put the single market in place. The goal of the ESEM is to promote efficient trading between price zones through increased electricity interconnection.[2]

The integration of the electricity market is crucial to integrate renewable generation, enhance security of supply across zones and achieve price convergence.

The latter aspect is the focus of this paper, i.e. we use a unit commitment model to study the impact of a new 700MW interconnector between the Single Electricity Market of Ireland and Northern Ireland (SEM) and France on wholesale electricity prices, generators' profits, system CO_2 emissions and welfare changes in the two markets.[3] We investigate the impact of this additional interconnection on the European electricity system considered as a whole in 2030. Finally, we also evaluate the welfare impact of interconnection in the presence of increased battery storage.

Many studies investigate the effects of interconnection on parts of the EU electricity systems. Newbery et al. (2016) provide a survey on the benefits of market coupling in Europe and discuss extensively the benefits of interconnection on balancing market integration. Konstantelos et al. (2017) focus on the North Sea region and analyse the costs and benefits associated with interconnection expansion in the Scandinavian countries. They find that increased transmission allows for better integration of renewables as it usually lowers the rate of curtailment, but can also lead to lower prices. Egerer et al. (2013) evaluates the welfare effects for the North Sea region of a grid expansion across Europe. The authors use a welfare-maximization algorithm to compare the effects on consumers, producers and congestion of an European mashed grid and bilateral projects. They find that mashed grids are welfare improving at the European level but have not always positive effects at the country level. However, no costs associated to the investment in additional interconnection are considered in this paper. Pellini (2012) analyses the impact of higher interconnection between Italy and central Europe on consumers, producers and congestion. She finds that market coupling is welfare improving if both demand and fuel prices increase.

Specifically on the interconnection between the island of Ireland and GB, SEM Committee (2011) shows that potential welfare gains associated with interconnection were

---

[1] See Commission (2012) and Eirgrid(2016)

[2] See Directive 2009/72/EC on common rules for the internal market and Regulation (EC) 713/2009, which established the Agency for Cooperation of Energy Regulators. On the transition from regional to single market see: `http://ec.europa.eu/energy/sites/ener/files/documents/2010_gas_electricity_markets.pdf`

[3] The Irish Single Electricity Market (SEM) is dispatched considering the two jurisdictions together (the all-island system). More information on the Irish SEM can be found here: `https://www.semcommittee.com/`. On the relevance of unit commitment models in studying systems with large proportion of renewable generation see Shortt et al. (2013).

in the magnitude of 30 €/million per year, without considering the investment costs associated with interconnection. Malaguzzi-Valeri (2009) focuses on SEM and GB and investigates the welfare effects associated to additional interconnection between the two jurisdictions. She finds that in order to achieve price convergence between the two markets interconnector's capacity should be at least of 500MW and that incentives for interconnection increase when technological differences between the two countries are large.

Diffney et al. (2009) and Foley et al. (2013) study how wind generation in SEM could be better integrated with new interconnection between SEM and GB. They also find that incentives in new interconnection decrease with technologies in the two countries are similar.

Finally, focusing on the interaction between storage and interconnection, Evangelopoulos et al. (2016) provides a survey of the methods that can be used to investigate the relation between the two technologies. Pudjianto et al. (2014) analyse the interaction between storage and interconnection for Europe up to 2020. The authors find that if the two investments are undertaken at the same time, energy storage reduces the costs of interconnection. Both papers analyse the impact on storage and interconnection on system flexibility but so far, we are not aware about contributions that analyse also welfare changes disentangling the effects on consumers and producers.

Our paper add novelty to the existing literature in several aspects. First, it provides a sound analysis on costs and benefits for consumers, generators and interconnectors' owners. Second our analysis focuses on the island of Ireland and France, but models the EU electricity system as a whole. Thus, our work studies the effects of a new transmission line also on the net revenues of existing interconnectors. At the best of our knowledge this issue has not been studied in other works. Third, it analyses possible interactions between storage and interconnection at the EU level, comparing the welfare changes for France and the island of Ireland when both technologies are adopted.

Our results show that without considering investment costs, the additional interconnector between France and SEM, Irish consumers are better off and the benefits to consumers more than offset the losses incurred by SEM generators. French producers and consumers are not significantly impacted.

When estimating the impact of the additional interconnector on the returns to all interconnector operators, we assume that any costs or benefits will be evenly split between the two connected countries. In SEM, on average net benefits increase for interconnector owners. In France there is basically no effect for consumers and producers but the owners of the transmission lines between France and other EU countries (included the additional line with SEM) increase their net revenues.

We then consider the costs associated with the investment in the additional interconnection. This offsets the welfare gains for both countries. In particular, SEM is near cost neutral for the scenarios examined. France has positive gains in one scenario.

We undertake a similar analysis considering increased storage (0.5GW for SEM and 11GW for France, equal to the 10% of the assumed peak demand in both countries), to verify the combined effect on welfare of both storage and increased interconnection. We assume that lithium batteries are installed by the consumers, and we find that increased storage both with and without additional interconnection significantly decreases wholesale electricity prices in both countries. However, the sequencing and timing of investment may be important. If investment in storage is made after the investment in interconnection, then the consequences on welfare become uncertain.

The paper is structured as follows: section 2 highlights the methodology, section 3 the data. Section 4 discusses the results of additional interconnection and section 5 shows the results with additional storage. Section 6 concludes.

2 Methodology

The software used to model the EU electricity market is the PLEXOS Integrated Energy Model.[4].The PLEXOS software is available from Energy Exemplar. PLEXOS is a tool used for electricity and gas market modelling and planning. In this analysis, the focus is limited to the electricity system, i.e. gas infrastructure and delivery is not considered. The methodology used to develop this European model is as presented in Collins et al. (2015).

The model minimises the overall generation costs across the EU to meet demand at an hourly resolution and subject to generator technical characteristics. These include operational costs, which consist of fuel costs and carbon dioxide permits, and start-up costs, which consist of a fuel and a fixed unit start-up cost. Variable renewable curtailment levels are low in the model and no inertia constraints are imposed in the model. Model equations can be found Deane et al. (2014).

In these simulations a competitive market is assumed across the EU (i.e. no market power and power plants bid their short run marginal cost) and we assume perfect foresight, whereby the model has full knowledge of all input variables such as demand and variable renewable generation output. This hypothesis does not allow us to investigate the potential beneficial effects of competition in mitigating anti-competitive behaviour in the two markets, as noted by Neuhoff et al. (2005). However, the regulation of the Irish Single Electricity Market (SEM) guaranteed that the outcome of the market was quite close to the outcome with the hypothesis of perfect competition, as shown by Walsh et al. (2016). The Irish SEM is currently under transformation, in order to become compliant with the EU targets for the ESEM. Here we assume that the transformation of the market structure does not affect market competition, but some concerns in this regard have been reported by Di Cosmo and Lynch (2016).

We simulate the full EU interconnected electricity market for one year (2030) at hourly resolution considering both variable renewable and thermal generation plants. Like all modelling exercises, the results in this study have to be interpreted in the context of the

---

[4] `http://energyexemplar.com/`. The full model and data used are available via `https://www.dropbox.com/sh/1xhjk3e19xc7xdq/AACS8ln_sjt3Aa_zSj7nzRYoa?dl=0`

modelling assumptions. First, one year of wind and solar profiles has been examined and therefore inter-annual variations in generation output have not been captured. Renewable generators have standard technical characteristics for each Member State.[5] Second, we use a static model, focusing on 2030 only. Third, demand is kept constant in the different scenarios we explore. Finally, our results are driven by our assumptions on fuel prices, demand profiles, portfolio and assumed interest rate and investment costs.

3 Data

The analysed power system is based on recent European Commission modelling of a Reference Scenario (PRIMES) of the future European Energy system and we consider 3 fuel price scenarios. [6]

The Reference Scenario is one vision of what the European power system might look like in 2030 based on business-as-usual assumptions, including full implementation of European climate and energy policies adopted by December 2014 to achieve a renewable electricity penetration of 42.5% in 2030 up from 27.5% in 2014.[7] This pathway can be interpreted as a lower bound on the emission reduction ambition within Europe, as we expect that further emission-abatement policies will be implemented prior to 2030. Approximately 2,220 individual thermal power plants are included in the model. The resulting market price is defined as the marginal price (note that this is often called the shadow price of electricity) at member state level and does not include any extra revenues from potential balancing, reserve or capacity markets or costs such as grid infrastructure cost, capital costs or taxes. These additional revenues or costs are not considered in this study.

The paper also investigates the welfare effects of increased storage and how it interacts with interconnection.[8] To determine the impact of increased levels of variable renewable generation, we need to set specific levels of CO_2 emission permit prices and fuel costs. Annual carbon dioxide permit (equivalent to ETS price) are set at €37.1/tonne in 2030 (in 2010 prices), consistently with the PRIMES 2016 results. Fuel prices across the scenarios are summarised in Table 1. Generators' costs are determined from the fuel costs, the emission costs and the average heat rate.[9] Average production costs inclusive of CO_2 for SEM and France are shown in Table 2 are based on three different fuel cost scenarios.

---

[5] Maximum capacity, minimum stable factors, ramp rates, maintenance rates, forced outage rates, start costs etc.

[6] PRIMES is a partial equilibrium model that provides "projections of detailed energy balances, both for demand and supply, CO_2 emissions, investment in demand and supply, energy technology penetration, prices and costs". The projections are set up in order to meet the EU targets on emissions for 2030:`http://ec.europa.eu/environment/archives/air/models/primes.htm`.

[7] The generation mixes of Switzerland and Norway are not included in the PRIMES scenario and were developed based on ENTSOE (2016) and Energiewende (2015).

[8] Battery storage included here is used to smooth daily demand peaks

[9] Production costs for power plant type i, inclusive of CO_2, are calculated as:

$$ProdCost_i = FuelPrice_i * HeatRate_i + ETS * (HeatRate_i * CO_2EmissRate_i) \quad (1)$$

CO_2 emission rates are 93.6 kg/GJ for coal, 55.9 kg/GJ for gas and 77 kg/GJ for oil.

European Commission has only one fuel price scenario, close to Scenario 2 (S2) we consider here. In order to allow the fuel prices to vary, we based our analysis on DECC (2016).[10]

Table 1: Fuel prices, (€2010)

€/GJ	Gas (CCGT, OCGT, derived gas)	Coal	Oil	Nuclear
Scenario 1	5.73	2.39	9.98	1.87
Scenario 2	8.47	2.94	14.75	1.87
Scenario 3	12.32	3.69	21.47	1.87

Data source: DECC (2016). Exchange rate €/GBP=0.858

Gas and coal prices are assumed to increase between Scenario1 (S1) and Scenario3 (S3), driven by carbon prices, however increases are not proportional. In S1 the short run marginal cost of gas fired generators is lower than the short run marginal cost of coal fired generators. In S2, the short run marginal cost of both fuels is similar and in S3 coal fired generation costs are lower than gas, as shown in Table 2. This has important implications for the dynamic of interconnector flows in each scenario.

Table 2: Short run marginal costs by fuel, SEM and France, (€2010)

(a) SEM

€/ MWh	Gas	Coal	Oil	Nuclear
S1	53.37	68.49	114.72	-
S2	72.08	74.95	157.30	-
S3	98.44	83.86	217.28	-

(b) France

€/ MWh	Gas	Coal	Oil	Nuclear
S1	53.25	69.35	108.6	20.10
S2	71.91	75.89	148.9	20.10
S3	98.21	84.91	205.7	20.10

3.0.1 Electricity generation capacity portfolio

The portfolio of the thermal power plants was chosen as it is consistent with EU policies at the time of writing. On the generation side, the PLEXOS-EU model used in this study utilises localised aggregate wind and solar generation profiles for each European Member State. Hourly wind power generation for each Member States was taken from Aparicio et al. (2016). Localised hourly solar profiles for each Member State were developed using NREL's PVWatts® Calculator web application, which determines the electricity production of photovoltaic systems based on system location and basic system design parameters.

Nuclear power has the largest share of the market in France, where in SEM natural gas is the main source powering thermal generation. Wind capacity is high in both countries,

---

[10] The European Commission release only one set of prices, available at `http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52014SC0015&from=EN`; the other prices are taken from DECC (2016)

with 6.1 GW of capacity installed in SEM and 30.7 GW installed in France. However, once the percentage of capacity is considered in relation to the overall capacity installed, the impact of wind is much higher in SEM than in France, as shown by Table 3.[11] The European "Reference" scenario is different from the generation portfolio of the two countries in 2012. Solar capacity was not installed in SEM in 2012, but in 2030 scenario increases to 0.2% of total capacity, with 22MW installed. The island of Ireland has an assumed installed renewable electricity capacity of 53%, or 43% of annual electricity generation by 2030, mainly driven by wind generation. France is dominated by nuclear both in 2012 and in 2030, but solar and wind capacity and other renewables increase significantly by 2030 climbing to approximately 50% of installed capacity by 2030 or 38% of annual electricity generation by 2030.

Table 3: % installed capacity on total capacity (MW), SEM and France, 2012 and 2030

	SEM		**France**	
	2012	**2030**	**2012**	**2030**
Coal	11%	7%	6%	2%
Natural Gas (OCGT+CCGT)	45%	33%	8%	5%
Oil and distillate	9%	4%	7%	1%
Hydro	2%	2%	20%	15%
Biomass Waste	1%	2%	-	2%
Solar	-	0,2%	3%	16%
Wind	20%	50%	6%	20%
Other Res	2%	0,3%	1%	1%
Peat	3%	-	-	-
Nuclear	-	-	49%	38%
CT	7%	-	-	-

3.1 Network

Interconnection between Member States is modelled as net transfer capacities and no transmission lines within the same country are considered. The electricity network expansion is aligned with the latest reference capacities for the year 2030 from the 10 Year Network Development Plan from ENTSOE (2016), without making any judgement on the likelihood of certain projects materialising, as shown in Figure 1. The same Figure shows that France is extensively interconnected with other European countries, as we consider interconnection lines between France and Spain (4GW), Italy (4.3GW), Great Britain (5.4GW), Germany (4.8GW), Switzerland (3.7GW), Luxembourg (0.3GW) and Belgium (4.3GW), for a total amount of 28.8GW.[12] SEM is only interconnected with Great Britain, with two interconnectors for a total capacity of 900MW. As a result, the new intercon-

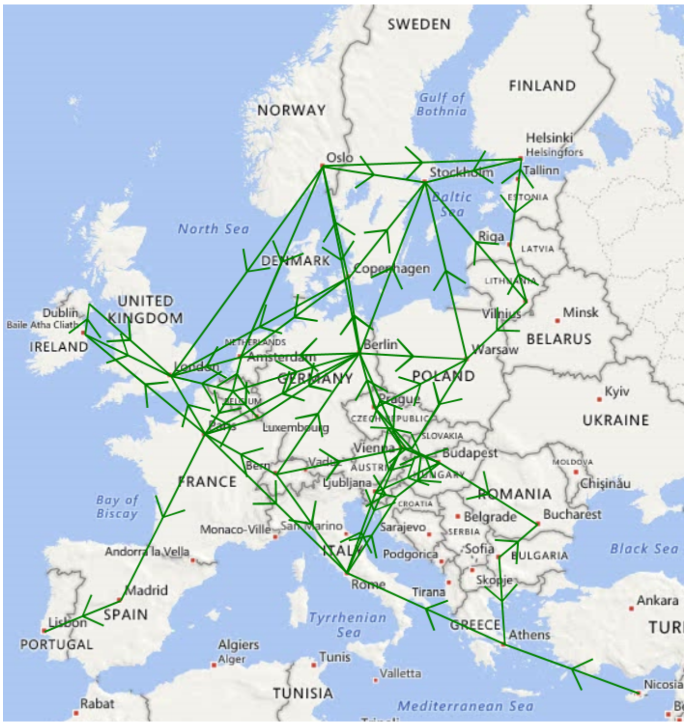
---

[11] On the absence of market power in the Irish SEM see Walsh et al. (2016).

[12] Some transmission lines have different export and import capacity. The full data set is available as supplementary information

nection project between France and SEM almost double the interconnector capacity for SEM, but will only represent the 4% increase in interconnection capacity for France.

Figure 1: Interconnection as modelled with the EU28 (plus Norway and Switzerland) Power System Model

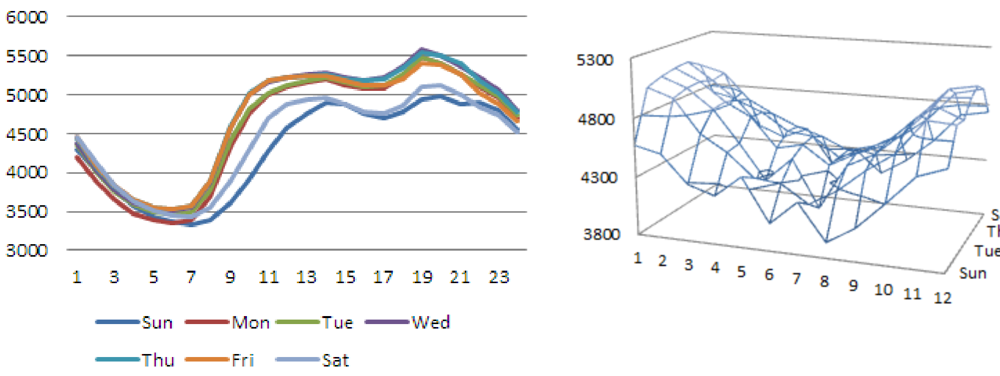


Note that arrows are for illustrative purposes only

3.2 Demand

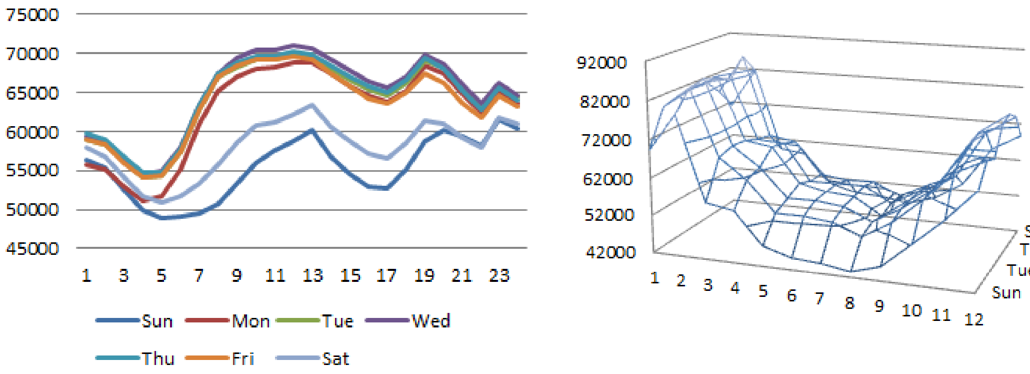
Hourly demand for 2030 for each member state was developed by taking the historical 2012 hourly demand reported in ENTSOE for the EU-28 plus Switzerland and Norway and scaling it to 2030. We assume that peak increases by 10% in 2030, and we linearly scale the demand accordingly. In the Reference Scenario examined, electricity demand across the EU rises by 12% between 2012 and 2030. For the purpose of this study, demand is assumed inelastic with respect to price; as a result, we use the same demand independent of changes in price across all our scenarios.

Figure 2: *Electricity Demand, SEM and France, MW, 2030, hourly averages.*



(a) *SEM,by day of week and hour (MW)*

(b) *SEM, by day of week and months (MW)*



(c) *France, by day of week and hour (MW)*

(d) *France, by day of week and months,(MW)*

Comparing Figure 2b and 2d shows that the seasonal variation in the consumption of electricity for SEM is lower than in France. This reflects the shape of electricity demand in 2012 in these two countries. In SEM there are no spikes in summer as the use of air conditioning is very low. The French electricity system is quite electrified; as a result, spikes both during the winter and during the summer are more frequent than in the island of Ireland.

4 Results and discussion: interconnection

In this section we focus on the effects of the investment in a 700MW interconnector between SEM and France. Results with both additional interconnection and additional storage are presented in section 5. Added interconnection in our model increases price convergence between SEM and France. A brief overview of interconnector's flows of the three scenarios considered in this study with their implications is presented below.

Scenario 1: In Scenario 1 (S1) the cost of generating with coal is higher than generating with gas. France is a net exporter of electricity, and the price differential between gas and coal drives the amount of exports to neighbouring countries such as Germany. In the baseline, without the additional interconnection between France and SEM, Germany has over 36GW of installed coal fired capacity representing 25% of installed capacity and net imports account for 7% of demand, with a capacity factor of 20%. Movements of the price of coal have a big impact on how coal plants operate. In S1, French coal plants operate at a capacity factor of 40%. With the inclusion of the IC to France, SEM becomes a net importer of energy from France for the portfolios examined, particularly in summers months when renewable generation in SEM is low and prices in SEM are relatively higher than in winter months. The imports from France reduce the wholesale electricity prices in SEM by reducing the full load hours and capacity factors of thermal generation. Moreover, the addition of the IC to SEM from France influences other IC lines. Flows from France to GB and Germany are reduced by 7% with minor influences on other lines. Net revenues of the owners of the transmission lines between France and the other EU countries and the net revenues of the owners of the lines between SEM and GB decrease with the additional interconnection between France and SEM.

Scenario 2: In Scenario 2 (S2), the cost of generating with coal and gas is similar for all the countries. Coal and gas prices are close with gas being marginally cheaper than coal. In this scenario German coal fired power plants increase output significantly to a capacity factor of 78%. Exports from France to Germany reduce (approx. 50%) and Germany becomes a net exporter (albeit very small, less than 1% of its demand). Flows from France into the UK, Italy and Spain decrease (<5%) and S2 sees the lowest levels of exports from France across all three scenarios. When the IC to SEM is added there is little change to the IC flow dynamics between France and other countries. In SEM natural gas CCGTs plants see a 3% reduction in annual capacity factor from 51% to 48% with the inclusion of the IC. SEM tends to export to France in winter months when wind generation is high and import from France at other times.

Scenario 3: In Scenario 3 (S3) coal prices are lower than gas across Europe. Germany increases coal plant output up to 43% in S3, and imports from France are reduced further, instead France exports to neighbouring countries with high levels of gas fired plant and low levels of coal capacity. The UK, Spain and Italy see increased imports from France compared to S1 and S2 . Overall net exports from France increase compared to S2 and S1(+14% in S3 with respect to S2). When the IC from SEM to France is added, Italy and Germany see a reduction of net imports from France. In Italy this reduction is compensated by an increase in gas fired CGCT's generation and in Germany a slight increase in coal fired generation is seen.

The following section analyses consumer surplus, the producers' and interconnector's owners' net revenues and the welfare changes from the "Baseline" scenario (without 700 France-Ireland interconnector) and the "IC" scenario.

4.1 Wholesale electricity prices and consumer surplus

Table 4b shows the wholesale electricity price for all the scenarios with the additional interconnection ("IC") of 700MW between SEM and France, and without IC ("Baseline").[13] The addition of the new interconnector reduces the wholesale electricity price in SEM by 4% in S1 and by 3% in S2, leaving wholesale prices almost unchanged in S3, when costs of gas plants are higher than coal fired plants. French wholesale prices are only marginally impacted.

Table 4a shows the total expenditure in electricity in million of euro in SEM and France. The difference in the expenditure levels from the "Baseline" to the "IC" scenario is the consumer surplus associated with the investment in the new 700MW interconnector, defined as:

$$CS_i = \sum_{h=1}^{8760} \Delta(p_{i,h} * L_{i,h}) \tag{2}$$

where h are the hours of the year, p_i is the load-weighted average price either in SEM or in France (i) and L are the total loads. Our model produces results for all the EU countries, as described in section 3.2. However, jurisdictions outside SEM, France and Great Britain (GB) are only marginally affected by the additional interconnection, so results for those countries are not shown in the paper.[14]

Table 4: Consumer surplus (Million Euro)and wholesale electricity price (€/MWh), 2030

(a) Consumer surplus(€/M), SEM and France

	S1			S2			S3		
	Baseline	IC	Δ%	Baseline	IC	Δ%	Baseline	IC	Δ%
SEM	2548	2452	3.9%	3222	3141	2.6%	4012	4013	0.01%
France	34253	34222	0.1%	41357	41513	0.4%	52889	52717	0.3%

(b) Wholesale electricity price (€/MWh) in SEM and France

	S1			S2			S3		
	Baseline	IC	Δ%	Baseline	IC	Δ%	Baseline	IC	Δ%
SEM	63,45	61,06	-3,91%	80,26	78,23	-2,59%	99,92	99,95	0,03%
France	63,11	63,05	-0,09%	76,20	76,49	0,38%	97,44	97,13	-0,32%

Baseline=No added interconn.; *IC*=With additional 700MW interconn.
$S1$=Scenario1:$Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2:$Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3:$Coal_{Cost} < Gas_{Cost}$

---

[13] Prices are calculated as load weighted averages: $p_{year} = \frac{p_h * L_h}{\sum_{h=1}^{8760} L_h}$ where h is the hour and L is the load

[14] The complete results are available from the authors upon request.

In S1, when the new interconnector is added, wholesale prices in SEM decrease by 3.9% with respect to the "Baseline". SEM sees a strong increase in both imports (+63%) and exports (+83%): exports are mainly in winter and imports in summer. This is mainly driven by wind generation, which is higher in winter than in summer, smoothing the winter demand's peaks. The consumer surplus reflects the price behaviour, increasing between 81 and 96 million euro in SEM in S1 and S2 and decreasing in France in S2. In S2 there is an increase in gas fired generation in France when the interconnector to SEM is added. This facilitates the exports to SEM, as gas cost in France is lower than in SEM (see Table 2). Consumers in SEM benefit most (i.e. consumer's surplus is largest) when coal generation costs are higher than CCGT generation costs as in S1, as the difference between the cost of coal and nuclear is higher than the difference between the cost of gas and nuclear. Also the operation of CCGT's in SEM is least impacted in S1 with respect to the other scenarios, and imports from France tend to replace more expensive coal generation. This is not the case in S2 and S3 where smaller margins and an inversion of costs between coal and gas leads to a larger displacement of CCGT generation in SEM.

Due to model size and sensitivity we consider relevant only variations greater than 1%. As a result, the interconnection between the island of Ireland and France does not change significantly the French prices and the French consumers'surplus.

We also analyse the impact of this interconnection on the GB electricity market as GB is connected with both SEM and France. Looking at GB, there is a small decrease in wholesale prices associated with a decrease in total generation costs. The added interconnector between SEM and France decreases the imports of electricity into GB from France. However, the trade between GB and the other other countries (such as Norway and the Netherlands) slightly increases, making the indirect effects of the new interconnector between France and SEM very small for GB.

4.2 Net revenue

In order to understand who gains and who loses from the investment in interconnection we calculate the net revenue obtained by the generators and by the interconnection owners. Here we consider a perfectly competitive energy-only market, so capacity payments or ancillary services are not taken into account in this analysis. Costs associated to the investment in the interconnector between SEM and France are not considered here, and counted separately in section 4.3.1.

4.2.1 Generators' net revenue

The generators' net revenue π is the sum of the net revenue made by each generator-types (coal, biomass, wind etc)s either in SEM or France (i) for each hour h of the year. The generator's net revenues π_{Gen} in country i in each scenario ("Baseline" and "IC") are defined as:

$$\pi_{Gen,i} = \sum_{s=1}^{N} \sum_{h=1}^{8760} (p_{i,h} * Gen_{s,h,i}) - TC_{s,h,i} \tag{3}$$

where $p_{i,h}$ is the electricity price in country i, $Gen_{s,h,i}$ is the generation in MWh for each of the N generators in each country, $TC_{s,h,i}$ are the total costs of each generator-type s in country i for hour h, defined as: $TC = (StartUpCosts + EmissionsCosts + FuelCosts)$. We then calculate the difference in yearly net revenue (Δ_π) between the IC and the baseline cases.

$$\Delta_\pi = \pi_{Gen,i,IC} - \pi_{Gen,i,Base} \tag{4}$$

where $\pi_{Gen,i,IC}$ is the net revenues made by generators in country i with additional interconnection and $\pi_{Gen,i,Base}$ is the net revenues in the same country without interconnection.

Table 5 shows the net revenues aggregated over all generators in each jurisdiction, and Table 6 disentangles the net revenues between renewable and thermal generators. The "Baseline" scenario is in the first column, with the "IC" scenario in the second.

Table 5: Generators net revenue, millions of €

	S1			S2			S3		
	Baseline	IC	Δ%	Baseline	IC	Δ%	Baseline	IC	Δ%
SEM	1347	1289	-4.5%	1666	1611	-3.5%	2019	2052	1.6%
France	28236	28252	0.1%	35793	36013	0.6%	48394	48238	-0.3%

Baseline=No added interconn.; *IC*=With additional 700MW interconn.
$S1$=Scenario1:$Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2:$Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3:$Coal_{Cost} < Gas_{Cost}$

Electricity generation by plant type both in the "Baseline" and in the "IC" scenarios is shown in Tables A1 and A2 in Appendix A.

Thermal generators in SEM end up with lower net revenues in S1 and S2, as the system imports more electricity from abroad and thermal plants are used less (see Table 5). In S1 this is most pronounced however in S2 and S3 this impact is softened as losses from gas fired generators (both CCGT and OCGT) are offset by increases in coal fired production and higher wholesale electricity prices. In France, net revenues do not change significantly (i.e. less than 1%) neither for nuclear nor renewable generators from the "Baseline" to the "IC" scenario. Net revenue for thermal producers reduces for France for different reasons: in S1 production declines. In S2, wholesale prices decreases and in S3 generation costs are higher in the "IC" scenario than in the baseline, as shown in Table B3 in Appendix B.

Table 6: Thermal and RES generators, net revenue, millions of euros

(a) Thermal producers

	S1			S2			S3		
	Baseline	IC	Δ%	Baseline	IC	Δ%	Baseline	IC	Δ%
SEM	226	154	-46.6%	209	146	-43.4%	209	181	-15.4%
France	346	337	-2.7%	261	250	-4.5%	489	477	-2.6%
Nuclear (FR)	16557	16564	0.0%	21655	21790	0.6%	29925	29832	-0.3%

(b) RES producers

	S1			S2			S3		
	Baseline	IC	Δ%	Baseline	IC	Δ%	Baseline	IC	Δ%
SEM	1121	1135	1.2%	1457	1465	0.5%	1810	1870	3.2%
France	11332	11351	0.2%	13877	13973	0.7%	17980	17929	-0.3%

Baseline=No added interconn..; *IC*=With additional 700MW interconn.
$S1$=Scenario1, $Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2, $Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3, $Coal_{Cost} < Gas_{Cost}$

4.2.2 Interconnector net revenue

The new interconnector allows electricity to flow between SEM and France and in particular, SEM imports 1.5TWh in S1 and over 2TWh in S3. This reflects the fact that the new interconnector displaces the Irish thermal generation: the higher the fossil fuel costs, the higher the imports of electricity from France to SEM. With the Irish-French interconnector in place, exports from France to the other EU countries generally decrease by commensurate amounts in all the three scenarios. The interconnector operator's net revenue aggregated over all the interconnectors in a country is calculated as

$$\pi_{IC_i} = \sum_{h=1}^{8760} abs(p_{i,h} - p_{j,h}) * abs(NetImport_{j,h}) \tag{5}$$

in which i is either SEM or France and j are the countries interconnected with SEM or France. In the baseline scenarios SEM is only interconnected with GB whereas France is interconnected with several EU Member States (Great Britain, Germany, Spain, Italy and Belgium). abs is the absolute value of the price differential between the two countries considered and h is the hour. Net revenues of French and Irish interconnector owners are shown in Table 7. The columns for France show the net revenues of all the interconnectors between France and the rest of Europe, with the exception of SEM. The columns for SEM show the net revenues of the interconnectors with GB. The final column ("SEM-FR") shows the profits of the additional 700MW interconnection. When we calculate welfare changes by jurisdiction, we assign half of the IC costs and returns to the interconnector owner in each jurisdiction.[15]

Table 7: Interconnector's net revenues, millions of euro

Scenario	France-EU			SEM-GB			SEM-FR
	Baseline	IC	Δ	Baseline	IC	Δ	
S1	973	933	-40	29	13	-17	20
S2	726	723	-3	23	10	-13	22
S3	897	883	-14	23	10	-14	24

Baseline=No added interconn.; *IC*=With additional 700MW interconn.
$S1$=Scenario1:$Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2: $Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3:$Coal_{Cost} < Gas_{Cost}$
Net revenues of interconnector's owners have been split evenly between the interconnected countries

As shown by the Table above, the net revenues of the Irish-French interconnector owners are positive, and equal to to 20-24 €/M for each country, assuming the countries split the revenues evenly, as the total net revenue made by the interconnector is between 40-49 €/M, depending on the considered scenario.

Under the scenarios examined, the new interconnector between SEM and France is beneficial for the Irish owner and moderately beneficial for the French owner. The small effect of the additional interconnection in France can be explained considering that the capacity of the new transmission line (700MW) represents only 1% of 2030 French peak demand. The new interconnection reduces the gains for SEM on the line with UK, but these losses are offset by the gains made on the new interconnection line, as shown by the last two columns of Table 7. France has very moderate (but significant) gains from the new interconnection with SEM in both S2 and S3 (the gains are less than the 3% of the baseline in S2 and less than 2% in S3) and losses of less than 3% in S1. The small effect of additional interconnection in France can be explained considering that the capacity of the new transmission line (700MW) represents only 1% of 2030 French peak demand.

The baseline for France is different across the scenarios because of the complex dynamics of European interconnection flows linked to gas and coal costs. As described at the beginning of this Section, the relative price between gas and coal changes the role of France (from net exporter to net importer) for countries like Germany and Spain.

4.3 Welfare changes

It is possible to draw some conclusions on the total welfare changes in SEM and France for the scenarios considered in our analysis. We calculate the yearly welfare in the two

---

[15] For simplicity, Moyle and EWIC interconnectors between SEM and GB are considered together. As a result, we split evenly also the net revenues of these interconnectors between the Irish and the British TSOs. This is a lower bound estimates of the net revenues of the Irish TSO, which owns the 100% of the EWIC interconnector.

countries following Malaguzzi-Valeri (2009). The welfare in country i (SEM or France) in scenario j (without or with interconnection) is calculated as the sum of the interactions between the electricity price in the two scenarios and consumer's demand (consumer surplus), the generators' profits (losses) and the interconnectors gains (losses) as:

$$\Delta(W_i) = \Delta CS_i + \Delta\pi_{Gen,i} + \Delta\pi_{IC_i} \tag{6}$$

where CS is the consumer surplus defined in Eq. (2), $\pi_{Gen,i}$ is the generators' net revenue defined in Eq. (5) and π_{IC_i} is the interconnector's owner net revenue as defined in Eq.(5)

Here we show the results for each jurisdiction: so the net revenue for the IC owners in each country is the total net revenue divided by 2, as we assume that interconnection's costs and profits are split equally between the interconnected countries. For simplicity, in the "IC" scenario we also include the profits made on the SEM-FR interconnector. We calculate the net welfare for both countries and report the results in Table 8 below:

Table 8: Welfare changes, millions of euros

(a) France

	S1			S2			S3		
	Baseline	IC	**Δ%**	Baseline	IC	**Δ%**	Baseline	IC	**Δ%**
CS	34253	34222	**0.1%**	41357	41513	**-0.4%**	52889	52717	**0.3%**
$\pi_{\mathbf{Gener}}$	28236	28252	**0.1%**	35793	36013	**0.6%**	48394	48238	**-0.3%**
$\pi_{\mathbf{IC}}$	973	953	**-2.1%**	726	745	**2.5%**	897	908	**1.2%**
Δ Welfare			**27**			**83**			**26**

(b) SEM

	S1			S2			S3		
	Baseline	IC	**Δ%**	Baseline	IC	**Δ%**	Baseline	IC	**Δ%**
CS	2548	2452	**3.9%**	3222	3141	**2.6%**	4012	4013	**0.0%**
$\pi_{\mathbf{Gener}}$	1347	1289	**-4.5%**	1666	1611	**-3.5%**	2019	2052	**1.6%**
$\pi_{\mathbf{IC}}$	29	33	**10.3%**	23	32	**30.1%**	23	34	**31.3%**
Δ Welfare			**42**			**36**			**42**

Baseline=No added interconn..; *IC*=With additional 700MW interconn.
$S1$=Scenario1, $Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2, $Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3, $Coal_{Cost} < Gas_{Cost}$
CS=Consumer surplus; π_{Gener}=profits generators; π_{IC}=profits IC owner
Profits from the Irish-French interconnector shown in the last column of Table 7 have been added to the IC owner profits in the IC scenario.

The monetary savings associated with lower emissions in both countries are already included in the producer profits so we do not take them into account explicitly in the welfare analysis.

In the next section we include the costs of building the interconnection and draw some conclusions on the benefits associated with this investment. Table 8 shows that without including the costs associated with the investment, interconnection is beneficial for SEM and not significant for consumers and producers in France, with the exception of the interconnector's owner, who has moderate positive gains from the investment project in S2 and S3.

In SEM, without considering investment's costs, the interconnector owner largely benefits from the project. Consumers are moderately better off in S1 and S2, producers are slightly worse off with the exception of S3.

4.3.1 IC costs

We take the ENTSOE 10-year Network Development Plan for 2016 to obtain estimates of the costs associated with interconnector investment.[16] The total costs of the 700 MW project are estimated between €900 and 1200 million in 2014 values.[17] These costs include the costs of materials and assembly, the expected environmental and consenting costs, the costs of devices that have to be replaced during the lifetime of the interconnector and the dismantling and maintenance costs at the end of the lifetime of the interconnector. As our analysis is based on 2010 prices, we convert the 2014 values into 2010 prices using the consumer price index published by Eurostat and obtain total costs of the project, between 840 and 1120 million of euro.[18]

Following Malaguzzi-Valeri (2009), we calculate the annual costs of the interconnector assuming that the two countries split the costs evenly and an interest rate of 6,58%. For a 15 year loan, the yearly cost of financing the interconnector for the year 2030 varies between 90 and 120 millions of euro per year. Assuming that SEM and France share the costs evenly, the annual investment cost for the additional interconnection is between 45 and 60 million of euro/year. As a result, welfare gains are no greater and could be less than the investment costs.

However, Irish consumers and interconnector's owners benefit from the investment. If the costs of the interconnectors are paid by the consumers in their bill, Irish consumers still have a positive surplus in S1 and S2, but, once the cost of the project are taken into account, consumers' surplus does not compensate the losses made by thermal generators in these scenarios. Moreover, in S3 consumers's surplus becomes negative once costs of the investment are taken into account.

The assumption on the interest rate is arbitrary, but reflects the nature of the investment on the project. Lower interest rates lead to different results: an interest rate of 4% leads to moderate welfare gains for SEM if the costs of the project are close to 45 millions euro/year.

For France, the investment in new transmission capacity with SEM is welfare-improving

---

[16] The report was accessed on 14 June 2017 at: `https://www.entsoe.eu/publications/system-development-reports/tyndp/Pages/default.aspx`. We also checked the published reports of the 2016 network plan but in the published works available for 2016 the numbers for 2014 are confirmed.

[17] See pg. 149.

[18] The data can be found here: `http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tec00118&plugin=1`

in S2. When costs of coal are higher or lower than gas costs the system dynamics make the costs of investing in IC equal or slightly higher than the associated benefits. In S1 welfare gains are reduced by the losses of interconnection owners (driven by lower prices in Germany and UK). As a result, the costs of additional interconnection, which are generally borne by consumers in the two jurisdictions, offset the benefits in this scenario. The same happens in S3, in which the cost of the project overcomes the welfare gains.

5 Results and discussion: storage

In this section we consider the availability of lithium batteries for the consumers. Batteries may help consumers in smoothing their consumption from peak time to other hours of the day (Schroeder (2011) and Díaz-González et al. (2012)), leading to an electricity system where increasingly the "demand follows generation". We investigate how storage and interconnection between Ireland and France affect the welfare changes in these two countries and how these investments interact.

We assume that storage is equally available in all the 28 EU countries considered in our model, with a capacity of 10% of the maximum peak demand of each country.[19] This results in 0.5 GW of storage for SEM and 11 GW for France.

The choice of the storage capacity as 10% of the peak demand is quite arbitrary. This is a relatively simple method to simulate storage and will not reflect full system effects as it does not directly include a price response component (which is important with high levels of variable renewable generation) but provides a useful starting point in gauging the impact of storage from a system wide perspective.

We simulate two scenarios with storage, with and without interconnection, in order to capture interactions between interconnection and storage.

When storage is added to the scenarios it impacts more on the times of the day in which different plants generate rather than changing the overall generation mix. Across Europe, the net overall amount of exports and imports reduce between 5% and 8% in all scenarios with storage. An exception to this trend are Member States with high levels of coal and lignite, such as Germany, that tend to export more baseload power when storage is added. This is particularly true in scenarios S2 and S3 where the coal costs are almost equal to or lower than gas costs. In France the amount of net exports to neighboring countries reduces along with net imports. Increased imports from Germany are seen in S2 and S3 when storage is added. In the island of Ireland, net import and net exports reduce in all scenarios and this is to be expected as storage dampens price volatility and flatted price profiles.

---

[19] The only exceptions are Norway and Switzerland, which do not have storage, but these two countries can rely on hydro generation.

5.1 Wholesale electricity prices

Table 9 shows the wholesale electricity price for SEM and France with storage in both countries. We compare 3 scenarios: the "Baseline" scenario (as in Table 3), the "Storage only" and the "Storage and IC" scenarios.

In SEM, the electricity prices for the final consumers are lower with storage than in the "Baseline" scenario. Comparing Table 9 with Table 3 shows that the effect of storage on final price is very close to the price with increased interconnection. Finally, the combination of more interconnection and more storage gives the lowest prices regardless of the fuel costs.

As expected, in France the impact of storage (both alone and combined with additional interconnection) on electricity prices is stronger than the impact of additional interconnection alone in all the scenarios.

Table 9: Wholesale electricity prices (€/MWh) with storage, 2030

	S1			S2			S3		
	Baseline	Storage only	Storage and IC	Baseline	Storage only	Storage and IC	Baseline	Storage only	Storage and IC
SEM	63.45	61.13	58.25	80.26	77.56	75.97	99.92	99.02	98.53
France	63.11	60.29	60.39	76.20	72.79	73.28	97.44	93.92	94.10

Baseline=No added interconn.ection, no storage
$S1$=Scenario1, $Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2, $Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3, $Coal_{Cost} < Gas_{Cost}$

Storage actively contributes to the reduction of wholesale electricity prices by smoothing the daily peaks.

The following sections examine the net revenues of generators and IC owners with storage. Then we calculate the welfare changes and include the analysis of the costs associated with the investment in storage and investigate the joint effects of storage and additional interconnection between France and the island of Ireland.

5.2 Net revenues

We calculate again the revenue by generators and by the interconnector's owner following Eq.(3) and Eq.(5). As in the previous section, the generators' net revenues do not include capacity payments and we assume perfect foresight in our model.

5.2.1 Generator's net revenues

With storage, in the SEM, thermal and renewable generators' net revenue decreases across the scenarios reflecting the lower wholesale prices. However an increase in the net revenue of thermal generators is witnessed in S1 due to an increase in gas generation at off-peak times to meet extra demand.

Thermal generation increases in France. The decrease of net revenues for both thermal and renewable generators are due to the decrease in the wholesale prices. Adding interconnection to the scenario with storage does not change the direction or the magnitude of the results for SEM. As expected, results for France are largely driven by storage, which is 10% of the peak demand instead of additional interconnection, which is less than 1% of peak demand. Comparing the baseline with the scenario with storage, thermal generation decrease significantly both in SEM and France. As a result, net revenues for thermal generators reduce strongly in both countries when storage is considered.

Table 10: Thermal and RES generators, net revenue, millions of euros

(a) Thermal producers

	S1			S2			S3		
	Baseline	Storage only	Δ%	Baseline	Storage only	Δ%	Baseline	Storage only	Δ%
SEM	226	180	-25.3%	209	145	-44.4%	209	164	-27.3%
France	346	220	-57.8%	261	58	-350.2%	489	301	-62.4%
Nuclear (FR)	16557	15714	-5.4%	21655	20637	-4.9%	29925	28889	-3.6%

(b) RES producers

	S1			S2			S3		
	Baseline	Storage only	Δ%	Baseline	Storage only	Δ%	Baseline	Storage only	Δ%
SEM	1121	1101	-1.9%	1457	1446	-0.8%	1810	1854	2.4%
France	11332	11069	-2.4%	13877	13567	-2.3%	17980	17643	-1.9%

Baseline=No added interconn., no storage; *Storage only*= With additional storage
$S1$=Scenario1, $Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2, $Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3, $Coal_{Cost} < Gas_{Cost}$

5.2.2 IC net revenues

Here we compare the interconnector's net revenue in the scenario with additional storage and interconnection ("Storage and IC") with the scenario with only additional interconnection ("IC") discussed in the previous section and summarised in Table 7. Comparing the two scenarios, the net revenue of the owners of the Irish-French interconnector decreases in the "Storage and IC" scenario with respect to the "IC" scenario. This result holds for both SEM and France. In particular, net revenues for the owners of the French interconnectors between France and other EU countries reduce when storage is added to the system. This is because in our model storage is added to all the EU countries and so each EU country is able to manage its own generation internally and requires less interconnection.

Irish interconnection owners see reduced revenues both on interconnectors with GB and on the new interconnection line with France. This suggests that interconnection and storage should be considered more as substitute than complementary technologies. In particular, this conclusion fully holds under our assumption of low curtailment of renewable generation in all the scenarios. Under different assumptions, both interconnection and storage may help integrate renewable generation in a better manner.

Table 11: Interconnector's profits with storage. Millions of €

Scenario	France-EU			SEM-GB			SEM-FR		
	IC	Storage and IC	Δ	IC only	Storage and IC	Δ	IC	Storage and IC	Δ
S1	933	739	-194	13	10	-3	20	13	-7
S2	723	446	-277	10	8	-2	22	12	-11
S3	883	568	-316	10	7	-3	24	14	-10

Baseline=No added interconn., no storage; *Storage only*= With additional storage
$S1$=Scenario1:$Coal_{Cost} > Gas_{Cost}$; $S2$=Scenario2: $Coal_{Cost} \simeq Gas_{Cost}$; $S3$=Scenario3:$Coal_{Cost} < Gas_{Cost}$
Net revenues of interconnector's owners have been split evenly between the interconnected countries

Interconnection flows in the scenario with storage are about a third of their level without storage in S1, although they drop by only 20% in S3. When storage is included in the system and gas costs are lower than coal costs (S1), flows between SEM and France are equal to 0.5TWh, and to 1.8TWh in S3. Even if the flows in absolute values are lower than in the previous scenario, SEM is still a net importer and France a net exporter.

5.3 Welfare changes

To compare the welfare changes associated with the investment in storage, we consider the "Baseline", "Storage only" and "Storage and IC" scenarios. In the next section, we add the capital costs of storage and compare our findings with the results shown in section 4.5. Table 12 shows the absolute welfare changes in SEM and France with and without storage as well as the welfare changes associated with both storage and additional interconnection for S2. Results for S1 and S3 are shown in Tables C4 and C5 in the Appendix.

With storage, interconnector's owners and generators face reduced revenues both in SEM and in France. Consumers increase their surplus in all the three scenarios (S1-S3), as shown by Tables 12 and C5, and this compensates (in levels) the losses faced by generators, leading to a positive welfare change in SEM.

France has a negative welfare change of -37€/million in S1 and of -20 €/million in S3 (see Appendix C). In particular, the reduction of exports in the presence of storage reduces the generation from thermal generators in France and reduces their net revenue. Moreover, also the interconnector's owner reduce their revenues as the flows between EU countries decrease in all the scenarios.

Adding the 700MW interconnection between SEM and France in the scenario with storage (the "Storage and IC" scenario) increases the net revenues of the interconnector's owner, but the changes are only significant (i.e. higher than the 1%) in S1. As expected, there are not significant changes for French consumers and generators between the scenario with storage only and the scenario with both storage and SEM-FR interconnector.

Some interesting conclusions can be drawn by comparing the welfare changes in the two scenarios with interconnection (the "IC" and the "Storage and IC" scenario), shown in Table 8 and in Table 12. First, the consumer surplus is higher in the "Storage and IC" scenario than in the "IC" scenario examined in Section 4.3, for both the countries, independent of the fuel scenario considered. Second, in France, producers are better off in the "IC" scenario, because thermal generators benefit from the peaks in demand that are smoothed by storage in the "Storage and IC" scenario. Finally, the owners of the interconnector between France and SEM have lower benefits when storage is in the system than in the "IC" scenario, since price differences between the two jurisdictions are smaller with storage, as discussed in section 5.3. The results for the other two scenarios are shown in Table C5 in Appendix C.

Table 12: Welfare, millions of euros, Scenario2 ($Gas_{Cost} = Coal_{Cost}$)

(a) France

	Baseline	Storage Only	**Δ**	Storage + 700MW IC	**Δ**
CS	41357	39544	**4.6%**	39825	**-0.7%**
$\pi_{\mathbf{Gener}}$	35793	34262	**-4.5%**	34525	**0.8%**
$\pi_{\mathbf{IC}}$	726	461	**-57.6%**	458	**-0.6%**
Δ Welfare			**17**		**-21**

(b) SEM

	Baseline	Storage Only	**Δ**	Storage + 700MW IC	**Δ**
CS	3222	3120	**3.3%**	3053	**2.2%**
$\pi_{\mathbf{Gener}}$	1666	1591	**-4.8%**	1540	**-3.3%**
$\pi_{\mathbf{IC}}$	23	15	**-50.3%**	20	**22.7%**
Δ Welfare			**19**		**21**

Profits from the Irish-French interconnector have been added to the IC owner profits in the "Storage and IC scenario".
CS=Consumer surplus; π_{Gener}=profits generators; π_{IC}=profits IC owner

5.3.1 Storage costs

Storage can be provided by many different technologies. Here we focus on the capital costs of battery storage, a technology that is appropriate for intraday storage.

To evaluate the potential costs associated with demand shifting from storage, we assume that the storage will be battery based. Following the JRC Energy Technology Reference Indicator projections for 2010-2050, we assume that the cost of the lithium-ion batteries used by consumers in 2030 varies between 110 and 170 €/kW in 2013 prices.[20] We convert them into 2010 prices by using the consumer price index. Then we calculate the discounted cost of the investment assuming a life-cycle of 15 years. We assume that the costs of storage are paid by each country. As highlighted before, for this scenario we assume 0.5 GW and 11 GW of demand response (facilitated through storage) installed in SEM and France in 2030. The costs of storage, under these assumptions, varies between 13 and 19 €/GW. As result of different storage capacity installed, in SEM, the annual cost associated with an investment in battery storage with an interest rate of 6.58% and a loan of 15 years, varies between 6 and 10 millions. For France, the costs varies between 138 and 213 millions.

These assumptions makes the comparison with the investment in interconnection easier, but they must be considered an upper bound of the total costs. First, as discussed by La Monaca and Ryan (2017), if the batteries are bought by the consumers through their saving accounts the interest rate that should be considered is close to 0.55%. Second, the consumers may invest in batteries well before 2030. As a robustness check, then, we assume the interest rate of 0.55% and we also assume that just 1/10 of the batteries are bought in 2030 in the two countries, considering that consumers start buying them from 2020. With these assumptions, costs scale down to less than 1 million for Irish consumers and to 9-14 millions for French consumers.

Comparing results in Table 12 to the cost assumptions, the investment in storage is profitable for consumers in both countries, even if we consider the high interest rate of 6.58% and that all the batteries are bought in 2030. As a result, rational consumers should invest in this technology; if policy makers do not undertake the investment in interconnection, welfare gains are of 17€/million for France and 19€/million for SEM in S2 in the case of the interest rate of 6.58%. However, this should be considered an upper bound, as not all consumers will actually invest in storage technology. In the reality, only some of the total consumers (i.e. consumers with high electricity use) are likely to undertake the investment in storage. However, the policy makers should be aware of the consumers' behaviour in particular when planning the investment in interconnection.[21]

If the investment in interconnection is undertaken and storage is available, the final equilibrium is the one with both storage and interconnection, because of the consumers' choice of investing in batteries. Again, as an upper bound of the welfare changes in this case, France is negatively affected by the investment in interconnection (-21 €/million) and SEM has moderate welfare gains (21€/million). However, if the investment costs associated to the additional interconnection are taken into account (45-60 €million per

---

[20] `http://publications.jrc.ec.europa.eu/repository/handle/JRC92496`.

[21] We do not consider any type of subsidies for renewables up to 2030. We assume that subsidies for renewables are not available in 2030 and consumers do not have these payments in their bills.

year for each jurisdiction) welfare changes become negative in both juridictions.

As a result, if storage becomes available when the investment in additional interconnection between France and SEM has been already undertaken, generators and interconnection owner are not significantly affected in France, but has negative revenues in SEM.

However, the costs of investment in storage associated with the costs of additional interconnection generate welfare losses in both the countries, driven by the costs of interconnection.

6 Conclusions and policy implications

This paper investigates how increased interconnection and the availability of demand response through storage impacts on welfare in Ireland and France in 2030 for three scenarios of fuel prices. The European power system analysed is one vision of how the power system in Europe may develop.

Our results show that, without taking investment costs into account, welfare increases in both SEM and France when a 700MW interconnector is added between the two systems. Consumers, interconnector owners and renewable generators gain in this scenario, whereas thermal generators lose, because of increased imports from France.

As the policy makers have direct control on the investment in interconnection, they should be aware that under the considered assumptions, with the costs of the project equal to or greater than 45 €/million per year for each jurisdiction, the new interconnector does not bring overall welfare gains neither to the island of Ireland nor France, even if interconnector's owners and Irish consumers may partially benefit from this project.

Assuming that the costs of investment in additional interconnection are paid by the consumers in each jurisdiction with their electricity bills, Irish consumers still have a positive surplus in some of the scenarios considered (S1 and S2), but their surplus does not compensate the losses made by thermal generators. In S3 consumers' surplus becomes negative in SEM if consumers have to pay for interconnection.

In France, net welfare gains are not very large and they are offset by (half) the cost of building the IC.

Investment in storage has the potential to reduce wholesale electricity prices both in SEM and France.

In SEM, storage increases welfare in all the scenarios, also taking the costs of investment in this technology into account. The opposite would happen in France, where consumer surplus does not compensate the generators' losses in S1 and S3. France has moderate welfare gains with storage in S2 only, which becomes negative depending on the assumed interest rate on the cost of the investment.

Comparing the scenario with increased storage with the scenario of increased storage and additional interconnector, the interconnector owners and generators marginally increase their profits in both countries. However, their net revenues are significantly lower than in the scenario with only additional interconnection.

As a result, if storage becomes available at competitive prices when the investment in additional interconnection between France and SEM has already taken place generates welfare losses in both the countries.

Policy makers cannot prevent consumers from investing in storage, but they can control the investment in interconnection. As a result, if consumers invest in batteries (and they become available in the next 10 years at a price close to the one hypotized in our analysis) and the interconnection project is undertaken, the final equilibrium is not welfare improving. The consequences on consumers, generators and interconnectors'owners vary depending on the scenario considered.

Acknowledgements

Valeria Di Cosmo has received support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 703382. We thank the participants to 2016 FSR Climate Conference, Laura Malaguzzi Valeri, John Fitgerald, Valentin Bertsch, Muireann Lynch and John Curtis for helpful comments and suggestion. The authors are responsible for all remaining errors.

References

Aparicio, I. G., Zucker, A., Careri, F., Monforti, F., Huld, T., and Badger, J. (2016). Part i: Wind power generation european meteorological derived high resolution res generation time series for present and future scenarios. Technical Report EUR 28171 EN; 10.2790/831549, JRC (Joint Research Centre) EU Commission and Emhires dataset.

Collins, S., Deane, J., and Ø'Gallachóir, B. (2015). The eu energy system in 2030:investigating electricity sector challenges.

Commission, E. (2012). Making the internal energy market work. Technical Report COM/2012/0663, European Commission.

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., and Villafáfila-Robles, R. (2012). A review of energy storage technologies for wind power applications. *Renewable and Sustainable Energy Reviews*, 16(4):2154 – 2171.

Deane, J., Drayton, G., and lØ'Gallachóir, B. (2014). The impact of sub-hourly modelling in power systems with significant levels of renewable generation. *Applied Energy*, 113:152 – 158.

DECC (2016). Decc fossil fuel price projection. Technical report, Department of Energy and Climate Change UK.

Di Cosmo, V. and Lynch, M. Á. (2016). Competition and the single electricity market: Which lessons for ireland? *Utilities Policy*, 41:40 – 47.

Diffney, S., Gerald, J. F., Lyons, S., and Valeri, L. M. (2009). Investment in electricity infrastructure in a small isolated market: the case of ireland. *Oxford Review of Economic Policy*, 25(3):469.

Egerer, J., Kunz, F., and von Hirschhausen, C. (2013). Development scenarios for the north and baltic seas grid – a welfare economic analysis. *Utilities Policy*, 27:123 – 134.

Energiewende (2015). The european power system in 2030: Flexiblity challenges and integration benefits. Technical report, Agora Energiewende.

ENTSOE (2016). Ten year national developement plan 2016 scenario developement report. Technical report, ENTSOE.

Evangelopoulos, V. A., Georgilakis, P. S., and Hatziargyriou, N. D. (2016). Optimal operation of smart distribution networks: A review of models, methods and future research. *Electric Power Systems Research*, 140:95 – 106.

Foley, A., Gallachóir, B. Ó., McKeogh, E., Milborrow, D., and Leahy, P. (2013). Addressing the technical and market challenges to high wind power integration in ireland. *Renewable and Sustainable Energy Reviews*, 19:692 – 703.

Konstantelos, I., Pudjianto, D., Strbac, G., Decker, J. D., Joseph, P., Flament, A., Kreutzkamp, P., Genoese, F., Rehfeldt, L., Wallasch, A.-K., Gerdes, G., Jafar, M., Yang, Y., Tidemand, N., Jansen, J., Nieuwenhout, F., van der Welle, A., and Veum, K. (2017). Integrated north sea grids: The costs, the benefits and their distribution between countries. *Energy Policy*, 101:28 – 41.

La Monaca, S. and Ryan, L. (2017). Solar pv where the sun doesn't shine: Estimating the economic impacts of support schemes for residential pv with detailed net demand profiling. *Energy Policy*, 108:731 – 741.

Malaguzzi-Valeri, L. (2009). Welfare and competition effects of electricity interconnection between Ireland and Great Britain. *Energy Policy*, 37(11):4679 – 4688.

Neuhoff, K., Barquin, J., Boots, M. G., Ehrenmann, A., Hobbs, B. F., Rijkers, F. A., and Vázquez, M. (2005). Network-constrained cournot models of liberalized electricity markets: the devil is in the details. *Energy Economics*, 27(3):495 – 525.

Newbery, D., Strbac, G., and Viehoff, I. (2016). The benefits of integrating european electricity markets. *Energy Policy*, 94:253 – 263.

Pellini, E. (2012). Measuring the impact of market coupling on the italian electricity market. *Energy Policy*, 48:322 – 333. Special Section: Frontiers of Sustainability.

Pudjianto, D., Aunedi, M., Djapic, P., and Strbac, G. (2014). Whole-systems assessment of the value of energy storage in low-carbon electricity systems. *IEEE Transactions on Smart Grid*, 5(2):1098–1109.

Schroeder, A. (2011). Modeling storage and demand management in power distribution grids. *Applied Energy*, 88(12):4700 – 4712.

SEM Committee (2011). Proposed costs and estimation of benefits of the introduction of additional intra-day gate closures in the sem. Technical Report 11-023, SEM Committee.

Shortt, A., Kiviluoma, J., and O'Malley, M. (2013). Accommodating variability in generation planning. *IEEE Transactions on Power Systems*, 28(1):158–169.

Walsh, D., Malaguzzi Valeri, L., and Di Cosmo, V. (2016). Strategic bidding, wind ownership and regulation in a decentralised electricity market. MPRA Paper 71502, University Library of Munich, Germany.

Appendix A Generation

The following Tables show generation from thermal and renewable sources for SEM and France. In France, RES generation does not include nuclear generation.

Table A1: Thermal and RES generation, SEM, GWh

(a) Thermal producers

	S1			S2			S3		
	Baseline	IC	Δ	Baseline	IC	Δ	Baseline	IC	Δ
No Storage	19,257	18,546	- 711	19,550	17,776	- 1,774	20,355	18,530	- 1,825
Storage	19,105	18,622	- 483	19,456	17,832	- 1,624	20,505	18,749	- 1,756

(b) RES producers

	S1			S2			S3		
	Baseline	IC	Δ	Baseline	IC	Δ	Baseline	IC	Δ
No Storage	19,674	19,703	29	19,684	19,705	21	19,666	19,705	39
Storage	19,697	19,704	7	19,699	19,705	6	19,698	19,705	7

Table A2: Thermal and RES generation, France, GWh

(a) Thermal producers

	S1			S2			S3		
	Baseline	IC	Δ	Baseline	IC	Δ	Baseline	IC	Δ
No Storage	24,067	23,911	- 156	14,671	14,946	275	32,818	33,305	487
Storage	25,068	24,760	- 308	8,324	8,943	619	28,939	29,380	441

(b) RES producers (without nuclear)

	S1			S2			S3		
	Baseline	IC	Δ	Baseline	IC	Δ	Baseline	IC	Δ
No Storage	193,529	193,551	22	193,587	193,569	- 18	193,573	193,575	2
Storage	193,540	193,649	109	193,653	193,660	8	193,673	193,679	6

Appendix B IC only: Generation costs

Table B3: Generators’costs, €million

	Baseline	IC	Δ%	Baseline	IC	Δ%	Baseline	IC	Δ%
SEM	1.08	1.04	-4.75%	1.45	1.31	-10.60%	1.93	1.75	-10.60%
France	9.64	9.63	-0.15%	9.30	9.33	0.32%	11.08	11.12	0.42%

Appendix C Storage: welfare changes, low and high scenarios

Table C4: France

	Scenario1					Scenario3				
	Baseline	Storage Only	**Δ%**	Storage + 700MW IC	**Δ%**	Baseline	Storage Only	**Δ%**	Storage + 700MW IC	**Δ%**
CS	34253	32811	**4.4%**	32876	**-0.2%**	52889	51024	**3.7%**	51124	**-0.2%**
$\pi_{\textbf{Gener}}$	28236	27003	**-4.6%**	27095	**0.3%**	48394	46833	**-3.3%**	46943	**0.2%**
$\pi_{\textbf{IC}}$	973	727	**-33.9%**	752	**3.3%**	897	574	**-56.2%**	582	**1.3%**
ΔWelfare			**-37**		**52**			**-20**		**19**

Table C5: SEM

	Scenario1					Scenario3				
	Baseline	Storage Only	**Δ%**	Storage + 700MW IC	**Δ%**	Baseline	Storage Only	**Δ%**	Storage + 700MW IC	**Δ%**
CS	2548	2461	**3.5%**	2342	**5.1%**	4012	3981	**0.8%**	3958	**0.6%**
$\pi_{\textbf{Gener}}$	1347	1281	**-5.2%**	1199	**-6.9%**	2019	2019	**0.0%**	2014	**-0.2%**
$\pi_{\textbf{IC}}$	29	21	**-37.8%**	22	**4.5%**	23	14	**-70.2%**	21	**35.1%**
ΔWelfare			**12**		**38**			**20**		**26**

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series
Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/
http://labs.jstor.org/sustainability/

NOTE DI LAVORO PUBLISHED IN 2017

1.2017, SAS Series, Anna Alberini, Milan Ščasný, The Benefits of Avoiding Cancer (or Dying from Cancer): Evidence from a Four-country Study

2. 2017, ET Series, Cesare Dosi, Michele Moretto, Cost Uncertainty and Time Overruns in Public Procurement: a Scoring Auction for a Contract with Delay Penalties

3.2017, SAS Series, Gianni Guastella, Stefano Pareglio, Paolo Sckokai, A Spatial Econometric Analysis of Land Use Efficiency in Large and Small Municipalities

4.2017, ESP Series, Sara Brzuszkiewicz, The Social Contract in the MENA Region and the Energy Sector Reforms

5.2017, ET Series, Berno Buechel, Lydia Mechtenberg, The Swing Voter's Curse in Social Networks

6.2017, ET Series, Andrea Bastianin, Marzio Galeotti, Matteo Manera, Statistical and Economic Evaluation of Time Series Models for Forecasting Arrivals at Call Centers

7.2017, MITP Series, Robert C. Pietzcker, Falko Ueckerdt, Samuel Carrara, Harmen Sytze de Boer, Jacques Després, Shinichiro Fujimori, Nils Johnson, Alban Kitous, Yvonne Scholz, Patrick Sullivan, Gunnar Luderer, System Integration of Wind and Solar Power in Integrated Assessment

8.2017, MITP Series, Samuel Carrara, Thomas Longden, Freight Futures: The Potential Impact of Road Freight on Climate Policy

9.2017, ET Series, Claudio Morana, Giacomo Sbrana, Temperature Anomalies, Radiative Forcing and ENSO

10.2017, ESP Series, Valeria Di Cosmo, Laura Malaguzzi Valeri, Wind, Storage, Interconnection and the Cost of Electricity Generation

11.2017, EIA Series, Elisa Delpiazzo, Ramiro Parrado, Gabriele Standardi, Extending the Public Sector in the ICES Model with an Explicit Government Institution

12.2017, MITP Series, Bai-Chen Xie, Jie Gao, Shuang Zhang, ZhongXiang Zhang, What Factors Affect the Competiveness of Power Generation Sector in China? An Analysis Based on Game Cross-efficiency

13.2017, MITP Series, Stergios Athanasoglou, Valentina Bosetti, Laurent Drouet, A Simple Framework for Climate-Change Policy under Model Uncertainty

14.2017, MITP Series, Loïc Berger and Johannes Emmerling, Welfare as Simple(x) Equity Equivalents

15.2017, ET Series, Christoph M. Rheinberger, Felix Schläpfer, Michael Lobsiger, A Novel Approach to Estimating the Demand Value of Road Safety

16.2017, MITP Series, Giacomo Marangoni, Gauthier De Maere, Valentina Bosetti, Optimal Clean Energy R&D Investments Under Uncertainty

17.2017, SAS Series, Daniele Crotti, Elena Maggi, Urban Distribution Centres and Competition among Logistics Providers: a Hotelling Approach

18.2017, ESP Series, Quentin Perrier, The French Nuclear Bet

19.2017, EIA Series, Gabriele Standardi, Yiyong Cai, Sonia Yeh, Sensitivity of Modeling Results to Technological and Regional Details: The Case of Italy's Carbon Mitigation Policy

20.2017, EIA Series, Gregor Schwerhoff, Johanna Wehkamp, Export Tariffs Combined with Public Investments as a Forest Conservation Policy Instrument

21.2017, MITP Series, Wang Lu, Hao Yu, Wei Yi-Ming, How Do Regional Interactions in Space Affect China's Mitigation Targets and Economic Development?

22.2017, ET Series, Andrea Bastianin, Paolo Castelnovo, Massimo Florio, The Empirics of Regulatory Reforms Proxied by Categorical Variables: Recent Findings and Methodological Issues

23.2017, EIA Series, Martina Bozzola, Emanuele Massetti, Robert Mendelsohn, Fabian Capitanio, A Ricardian Analysis of the Impact of Climate Change on Italian Agriculture

24.2017, MITP Series, Tunç Durmaz, Aude Pommeret, Ian Ridley, Willingness to Pay for Solar Panels and Smart Grids

25.2017, SAS Series, Federica Cappelli, An Analysis of Water Security under Climate Change

26.2017, ET Series, Thomas Demuynck, P. Jean-Jacques Herings, Riccardo D. Saulle, Christian Seel, The Myopic Stable Set for Social Environments

27.2017, ET Series, Joosung Lee, Mechanisms with Referrals: VCG Mechanisms and Multilevel Mechanism

28.2017, ET Series, Sareh Vosooghi, Information Design In Coalition Formation Games

29.2017, ET Series, Marco A. Marini, Collusive Agreements in Vertically Differentiated Markets

30.2017, ET Series, Sonja Brangewitz, Behnud Mir Djawadi, Angelika Endres, Britta Hoyer, Network Formation and Disruption - An Experiment - Are Efficient Networks too Complex?

31.2017, ET Series, Francis Bloch, Anne van den Nouweland, Farsighted Stability with Heterogeneous Expectations

32.2017, ET Series, Lionel Richefort, Warm-Glow Giving in Networks with Multiple Public Goods

33.2017, SAS Series, Fabio Moliterni, Analysis of Public Subsidies to the Solar Energy Sector: Corruption and the Role of Institutions

34.2017, ET Series, P. Jean-Jacques Herings, Ana Mauleon, Vincent Vannetelbosch, Matching with Myopic and Farsighted Players

35.2017, ET Series, Jorge Marco, Renan Goetz, Tragedy of the Commons and Evolutionary Games in Social Networks: The Economics of Social Punishment

36.2017, ET Series, Xavier Pautrel, Environment, Health and Labor Market

37.2017, ESP Series, Valeria Di Cosmo, Sean Collins, and Paul Deane, The Effect of Increased Transmission and Storage in an Interconnected Europe: an Application to France and Ireland