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Investment with incomplete markets for risk: The need for long-term contracts☆

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ABSTRACT

Barring subsidies, investment in the power generation sector has come to an almost complete halt in the restructured European power sector. Market and regulatory failures such as the well known missing money (see Joskow, (2006)) but also normal market features such as risk, possibly also affected by market failures like market incompleteness are mentioned as common causes for the situation. This paper discusses incomplete risk trading and its impact on investment. The analysis applies computable stochastic equilibrium models on a simple market model of the Energy Only type. The paper first compares the cases of complete and fully incomplete markets (full risk trading and no risk trading). It continues by testing the impact of different risk trading contracts on both welfare and investment. We successively consider Contracts for Difference, Reliability Options with and without physical back up that we add to our Energy Only market model. We test the impact of market liquidity on the results. Finally, we compare these methods to a Forward Capacity Market that we also add to the energy only model. We complete the paper by interpretation of these results in terms of hurdle rate implied by these risk-trading situations.

1. Introduction

European investment in non-subsidized generating capacities has now come to an almost complete halt. Recent years have even seen a shift from investing to mothballing and anticipative retiring of technologically advanced plants. Various reasons explain this evolution. The familiar "missing money", the lower demand due to the economic situation and energy conservation as well as several market imperfections are often mentioned. The uncertainty surrounding the restructuring and energy transition processes and the economic recovery also play a role. We focus on long-term demand risk in energy only markets (EOM) and discard other considerations.

The importance of risk in investment pervades corporate finance since the early days of Management Science. Valuations of risky assets can roughly be classified in two major approaches. One is based on the so-called Capital Asset Pricing Model (CAPM) and is mainly used for long-term investment. The other is based on contingency pricing and the literature of derivative pricing: it is commonly applied for hedging short and medium-term operations (see Cochrane (2005) for an extensive discussion of both approaches and Eydeland and Wolyniec (2003) for the application of derivative pricing to power and gas). Derivative pricing is also used to value flexible power plants. "Reliability options" is a particularly original application of derivatives to remedy the missing money (Vasquez et al. (2002), Oren (2005), Chao and Wilson (2004) and more recently Pöyry (2015) and several other authors).

CAPM and contingency pricing are technically different but commonly applied under similar fundamental assumptions: both rely on exogenous (econometrically estimated) price processes and risk premium. Both also generally neglect issues of market incompleteness (see Magill and Quinzii (2002) for an extensive treatment in finite horizons). These simplifications were probably sufficient in the past but may now be inadequate in the highly uncertain context of the restructured power market.

This paper contributes to the literature by presenting different stochastic equilibrium problems to quantify the impact of risk, market incompleteness and contracts in investment in power generation. These models are easily interpretable in standard investment criteria and are treated in a single computational framework. We illustrate the approach on a stylized stochastic equilibrium investment problem for which we assume exogenous processes of fundamentals (such as demand and fuel costs). In contrast with most of the literature, we

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rely on the equilibrium context to endogenously derive stochastic electricity prices and risk premium together with investment (see Lopez-Pena et al. (2009) for an alternative treatment by System Dynamics). We also quantify the impact of various degrees of market incompleteness by introducing contracts in an otherwise incomplete market and assessing their impact compared to complete markets. While the underpinning economic notions (price taking agents, risk, market incompleteness, and hedging contracts) embedded in the model are standard, the equilibrium models and the underpinning computational approach are novel. They are general, based on powerful software and hence not limited to small examples.

The paper is formula free but based on fully formalized models. The mathematical formulation and its economic interpretation are given in de Maere d'Aertrycke et al. (2016). Technical results are presented in Abada et al. (2015) and (2016).

This paper analyses the impact of long-term demand risk on investment in energy only markets (EOM) where the missing money is corrected by a price cap. Taking stock of that basic framework we add risk mitigation instruments such as long-term contracts (contracts for differences (CfD), reliability options (RO) or forward capacity markets (FCM) under different assumptions of market liquidity). We complete the analysis by also considering a capacity market. We report welfare and investment levels. The analysis is conducted in an investment context; transposition to mothballing and anticipated decommissioning are more relevant today but probably also less usual in the literature. This transposition will be the subject of another paper.

The paper is structured as follows. Section 2 recalls the basic ideas underpinning investment problems in the different market settings. Section 3 introduces the methodology and the illustrative very simple physical model of generation and demand and the different instruments examined in the case study. We discuss the results in Section 4 with welfare and investment presented in unified graphic form for the different instruments. Section 5 reinterprets the analysis in more financial terms. Conclusions terminate the paper.

2. Background: investment problems in different market contexts

The discussion is conducted in a simple two-stage framework: one invests in period 0 and a power exchange (PX) clears the energy market in different time blocs in period 1.[1] Uncertainty is represented by a set of demand scenarios that each apply to the different times blocs of period 1. Each scenario reflect a load duration curve for a year (8760 h). The uncertainty is hence on the overall system evolution and not on the intra yearly uncertainty. Demand is exogenous and price inelastic. Agents are price taking.

2.1. The risk free world

Demand is deterministic and electricity prices are the sole drivers of investment in EOM. The standard criterion is to invest as long as the gross margin of the incremental equipment is greater than or equal to its capacity cost. The criterion depends on the cost of capital. It is equal to the risk free rate in a risk free world. As explained before the merit order determines electricity prices and generation quantities and hence revenue and operating costs and eventually gross margins.

The combination of the investment criterion and the merit order forms the equilibrium model in the risk free world. This equilibrium model can be solved by a standard capacity expansion optimization problem. From an economic point of the view the equilibrium model describes "perfect competition" where the producer and the consumer respectively maximize their profit and surplus taking prices as given. Note for the rest of the discussion that the equilibrium model simultaneously determines investment, operations and electricity prices. The endogenous price process is one of the important features of the equilibrium approach.

2.2. A risky world without contract

Economics and corporate finance have spent considerable effort for modelling risk and assessing its consequences. We restrict our discussion to a few elements. The standard practice is to account for risk by adding a risk premium to the risk free rate for computing the cost of capital. The risk premium is usually derived from historical data using the Capital Asset Pricing Model (CAPM). Future risk exposures in a restructured power sector undergoing the energy transition will be quite different from those of the past. We thus take the position that the computation of the cost of capital cannot be based on past data but must be endogenously determined by the model: new capacities influence their risk exposures, which implies that investment and cost of capital must be determined simultaneously. We briefly and verbally describe how this is done and refer the reader to Ehrenmann and Smeers (2011b), Ralph and Smeers (2015) and de Maere d'Aertrycke et al. (2016) for the technical development.

2.2.1. Risk neutral agents

Suppose first that investors facing the demand scenarios are risk-neutral. The investment criterion of the risk free world is modified as follows: one invests in some equipment as long as its expected gross margin computed for the different demand scenarios is larger than or equal to its capacity cost. This modified investment rule combined with the unchanged merit order rule defines the new equilibrium model.

This model simultaneously determines investment, generation and prices. These prices are defined for the different states of the world describing uncertainty and are endogenous to the system. Because agents are risk neutral the discount rate remains the risk free rate. The risk neutral stochastic model is well established (see for example Murphy et al. (1982) or Haurie et al. (1988)).

2.2.2. Risk averse agents

Neither investors nor consumers are risk neutral. The von Neumann-Morgenstern utility functions that appeared in economics in 1953 (van Neuman Morgenstern, 1953), and risk functions (Artzner et al., 1999) developed more recently in finance are two methods that associate a deterministic equivalent to risky payoffs. The latter is directly related to risk criteria used in risk management practice. We thus use a CVaR, which has become the most widely used coherent risk function (a function that satisfies the properties of monotonicity, sub-additivity, positive homogeneity, and translational invariance), and refer the reader to the general literature about coherent risk functions. The investment criterion is then restated as follows: one invests in a new equipment as long as the CVaR of its gross margin computed for the different demand scenarios is greater than or equal to its capacity cost. In other words in equilibrium for the investments decided by the model costs are equal to the risk adjusted expected gross margins hence the net present value is zero. Calculating the expected profit with the real probabilities ex-post leads to a positive net present value. The merit order completes this investment criterion to define the risk-averse equilibrium model. We mention for the sake of completeness that the model is no longer amenable to a solution by an optimization problem but can be written as equilibrium problems and refer the reader to our companion papers for further discussion.

Risk functions implicitly embed a risk premium: each agent discounts the expected value of the payoff by an endogenous premium that depends on its risk aversion and the risk pattern of its payoff. As with risk neutrality, prices are now defined in the different states of the world and are endogenous to the system. But because agents are risk averse the discount rate of each agent now becomes the sum of the risk

[1] In the real world, the investment stage (period 0) last 4–5 years while the operations phase (period 1) is 20 years long.

Table 1
Cost data for investment and operational costs. Availability is scenario depended and sampled from a normal distribution.

	Annuity	Variable	Availability	
	Euro/kw	Euro/MWh	Expected	std dev
base	110	30	80%	2%
peak	60	60	90%	5%

Table 2
Demand scenarios and segments. The l1 represents 10%, l2 30% and l3 60% of the time.

demand	l1	l2	l3
s1	9.856681	15.037	18.11079
s2	9.966767	14.5131	21.16283
s3	9.834117	15.22419	20.91238
s4	9.951644	15.03382	18.80235
s5	9.883665	14.4681	18.23711
s6	9.796393	15.34816	23.11438
s7	9.816114	15.54859	22.14536
s8	10.04581	14.68699	20.6993
s9	10.00309	14.53284	20.23061
s10	9.87731	14.36674	17.87016
s11	10.29804	15.36569	20.65747
s12	10.33165	15.10813	18.91329
s13	9.653905	14.80922	19.88592
s14	10.23679	14.42675	22.89554
s15	10.40406	14.8921	18.49179

free rate and the endogenous risk premium of the agent. Enabling endogenous prices and cost of capital of this equilibrium model significantly expands the traditional context of power investment found in the literature where power price distributions are usually taken as given (Roques et al. (2008)) for portfolio optimization in a mean variance approach or Fortin et al. (2007) for portfolio selection based on a CVAR. An exception can be found in recent study of Artelys (2015) that integrates the impact of investments on the risk profile and adjusts the investments accordingly.

2.3. A risky world with contracts

Risky markets commonly introduce hedging instruments. Short-term electricity markets developed derivatives of the forward and option types (Eydeland and Wolyniec, 2003). These instruments do not exist yet for the long term but their introduction has been proposed to incentivise investment. We follow suit and complement our electricity market by assuming that generators and consumers can trade opposite risk exposures (high prices favourable to generator but unfavourable to the consumer) through those instruments. Specifically generators and consumers take (opposite) positions in those instruments in period 0 and receive payments accruing from these positions in the time blocs of period 1 depending on the demand scenario. This requires modelling risk-averse consumers entering those transactions. We use the same risk function (CVaR) for both the generator and the consumer (this can be modified in implementation). The payoff accruing from these hedging instruments only depends on the spot price and is then entirely determined by the clearing of the market in period 1 in the different states of the world. We keep the electricity market clearing rule unchanged but note that the consumer now becomes an active agent (trading financial energy contracts). This implies modifying the investment criterion as follows.

The risk exposure of the generator is now a function of the payoff received from its plant and contractual positions. The generator then invests in an equipment as long as the CVaR of the gross margin of this equipment valued on the basis the global risk exposure (physical and

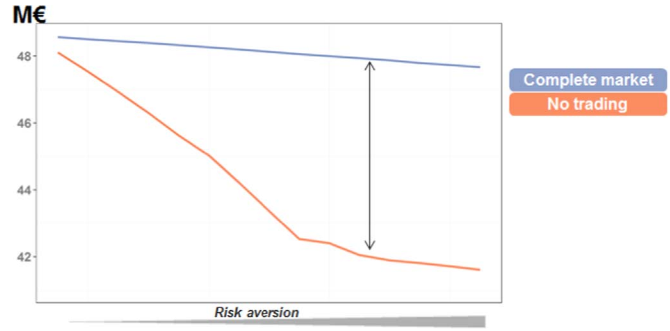

Fig. 1. Welfare as function of risk-aversion in the "complete" and "no risk trading" cases.

financial) of the generator is greater than or equal to the capacity cost of the equipment. Similarly the generator takes position in the contract as long as the CVaR of the payoff accruing from this contract is higher than the cost of the contract. The contractual positions of the generator and the consumer are in balance (no external speculator).

This situation is significantly more complex than the one without financial contract. One complication is that in contrast with physical equipment, which are characterized by exogenous capacity and fuel costs the prices of financial contracts are endogenous to the model. The second difficult is that financial products present risk of their own and in particular liquidity risks, which have shown devastating effects in the protracted financial crisis. This can in turn generate credit risk impacts. We briefly touch upon these problems, which should be kept in mind when confronted with financial products to remedy insufficient investments even if they are not explicitly considered in our numerical illustrations. For the theory and mathematical formulation we refer to Ralph D. and Y. Smeers (2015), de Maere d'Aertrycke et al. (2016).

2.4. Risk trading and related notions

Market risk induces the development of hedging instruments. Our concern here is long-term electricity price risk that influences the risk of new generation capacities. There is today no instrument for hedging this risk but some have been proposed. Specifically long-term contracts for differences (CfD) have been proposed and accepted by European competition authorities for guaranteeing the electricity price collected by nuclear units in the UK. Reliability option (RO) contracts have also been discussed to guarantee the financing of peak units in various places.

We consider an ideal (unrealistic) situation where all risk can be traded. This would be the case if it were possible to hedge all price and volume risks (and hence revenue risk) of each plant. This ideal market is known as "complete": it is relatively easy to simulate but impossible to implement in practice. Another extreme (unrealistic) case occurs when there are no hedging instruments on the market (unrealistic because some partial hedging through equities is always possible). This market (hereafter "no risk trading) can also be modelled but is more difficult to simulate. Power markets endowed with long-term CfDs or ROs offer intermediate hedging possibilities. We standardly refer to them as "incomplete" markets.

Contract trading may suffer from illiquidity. An investor interested in the contract may not find a counterparty or only one asking for a very high price. We model illiquidity in a particular simple way by a bound on the transactions that can done between producer and consumer. Long-term price risk may also lead to bankruptcy, introducing credit risk.

3. Methodology and case study

The following results are obtained from stochastic equilibrium models of risk averse agents presented elsewhere. Specifically "no risk

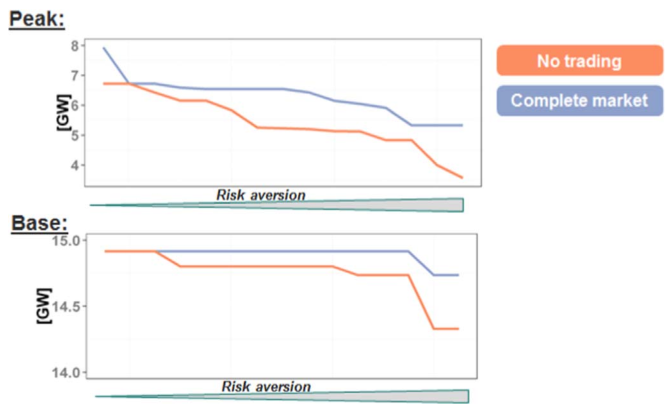

Fig. 2. Peak and base capacities as function of risk-aversion in the "complete" and "no risk trading" cases.

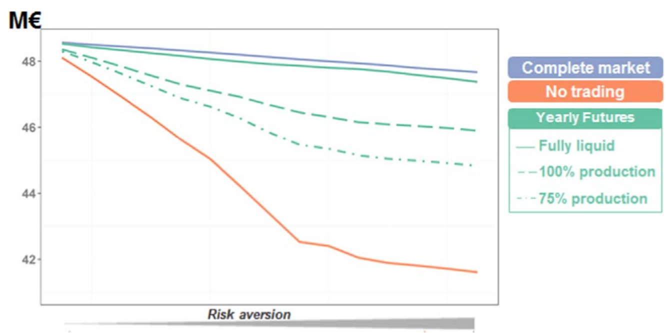

Fig. 3. Impact of yearly futures contract on the welfare as function of risk-aversion.

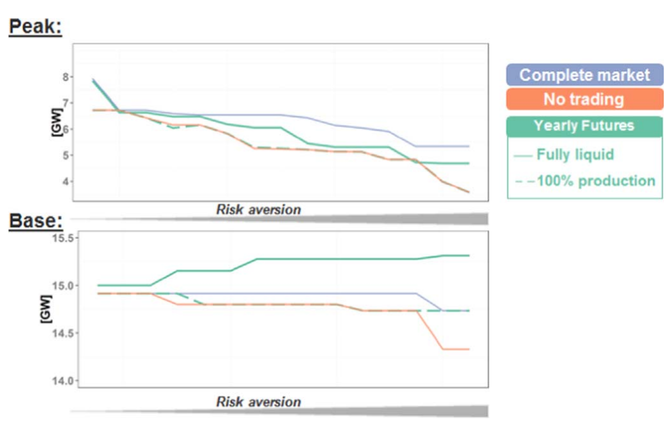

Fig. 4. Impact of yearly futures on the peak and the base capacities as function of risk aversion.

trading" appears in Ehrenmann and Smeers (2011a) (2011b) while "complete" is taken from Ralph and Smeers (2015). Models with tradable contracts and liquidity limits are given in de Maere d'Aertrycke et al. (2016). Detailed technical information (including properties of the modes like existence and uniqueness) is presented in Abada et al. (2015) and (2016).

3.1. Set-up of the case study

We consider a simple two-stage framework: one invests in period 0 and a PX clears the market in period 1, which is itself decomposed in three time blocs (peak, shoulder and base). Results are reported on a yearly basis for each period. The annual "investment cost" of a plant (in euro/kW) is derived from its overnight investment cost using its technical life and discount rate reflecting the risk free rate (a more detailed discussion in the pricing of systemic and idiosyncratic risk can be found in Ehrenmann and

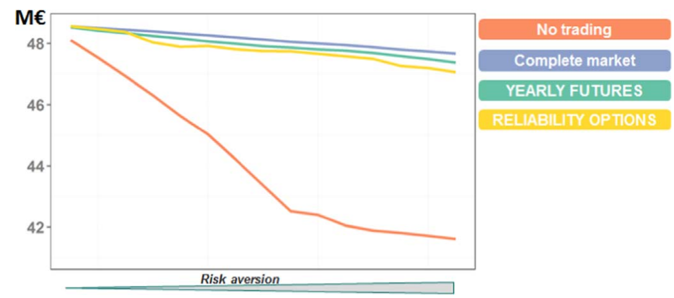

Fig. 5. Impact of reliability options on the welfare as function of risk-aversion.

Smeers (2011b)). The cost of capital will be part of the equilibrium and is discussed as we proceed. There are only two types of plants namely "base" and "peak". Capex are respectively 110 euro /kW for base and 60 euros per kW for peak. Variables costs are 30 and 60 euros/MWh for these plants respectively. The investment parameters are summarized in Table 1. Demand is inelastic except for curtailment when the price reaches a CAP taken at a very moderate 500 euros/MWh. We assume that the value of lost load is equal to the cap. This model is as simple as can be but the numerical machinery is general. Demand figures for the 15 scenarios are reported in Table 2.

We overlook indivisibilities and assume that the merit order prevails in each time bloc of period 1 with the consequence that the electricity price in the bloc is equal to the fuel cost of the marginal unit, except if there is curtailment and the price is set to the cap. This is how the traditional EOM eliminates the missing money. The gross margin (before investment costs) made by a plant in period 1 is equal to its total revenues minus its total operating cost. Its net margin is equal to its gross margin minus its investment cost. For the sake of simplification we only assume one generator and one consumer linked by the trade of energy and in some sections of the paper by contracts.

3.2. Risks

The generator invests in stage 0 before uncertainty on demand is revealed in stage 1. Demand uncertainty is interpreted as long-term (resulting from the combination of economic and policy uncertainty). It is described by 15 scenarios of annual load, each decomposed in three time blocs with a peak time bloc of 876 h or 10% of 8760 (the remaining time bloc cover 30% and 60% of the year). The generator is exposed to the volatility of its revenue and hence is concerned that it may be unable to recover its fixed costs. The consumer is exposed to

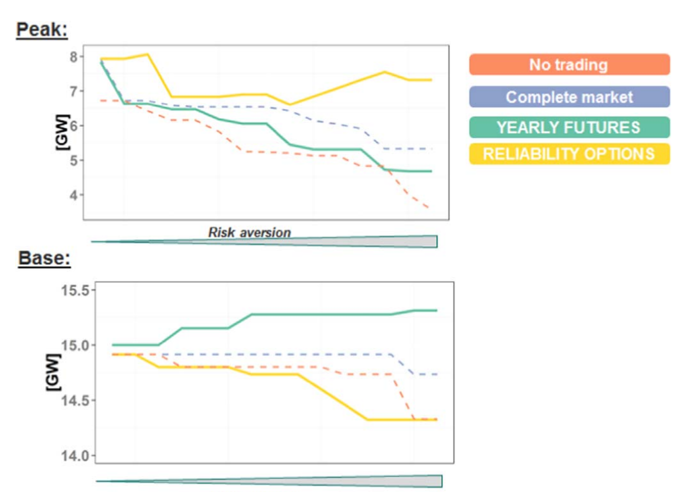

Fig. 6. Impact of reliability options on the peak and the base capacities as function of risk aversion.

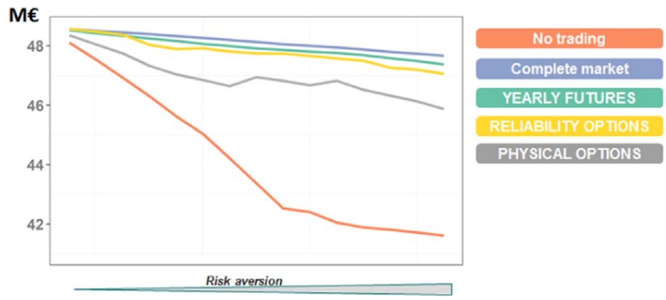

Fig. 7. Impact of physical options on the welfare as function of risk-aversion.

Fig. 8. Impact of physical options on the peak and the base capacities as function of risk aversion.

price spikes in stage 1, which creates volatility of its surplus ((CAP minus electricity price) times quantity). The objective of the paper is to explore how risk and hedging instruments affect adequacy. We measure "adequacy " as the amount of unserved load.

The simulation (but not the model itself) makes the economically common assumption that the market consists of several identical firms, which then see the same risk and can be aggregated in a single firm.

4. Model results and analysis

We first introduce the "complete" and "no risk trading" counter-factuals and then explore the impact of long-term CfD (Contract for Differences) and RO (Reliability Option) under different conditions of liquidity. We also consider a long-term FCM (Forward Capacity Market) for the sake of completeness. All instruments are added to the "no risk trading" case that represents a pure EOM. To simplify things, we suppose equal contract and plant lifes. Graphs report capacities and welfare information (sum of risk-adjusted values of

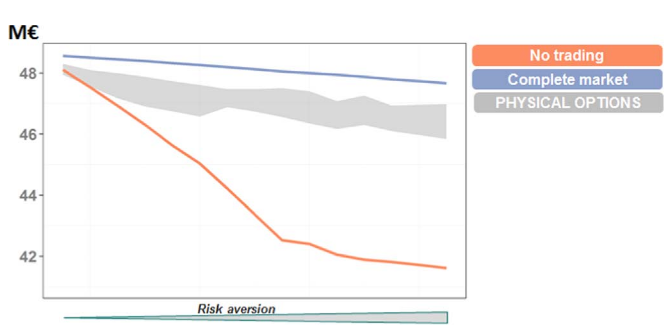

Fig. 9. Impact of penalities (between euro 100 and 1000 per missing MW) for physical options on the welfare as function of risk aversion.

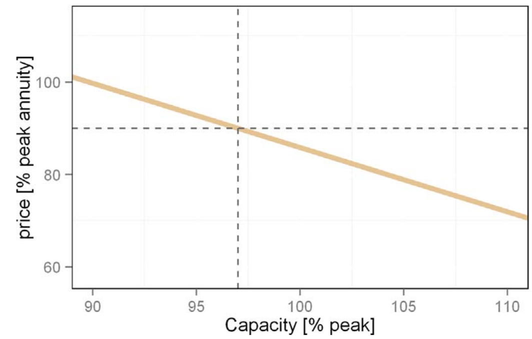

Fig. 10. Capacity demand curve.

the producer's profit and consumer's surplus) as function of risk aversion (increasing from left to right[2]).

Risk influences investment through its impact on the cost of capital or equivalently on the risk premium demanded by investors. We thus also report in a separate section the implicit risk premium associated to investments and discuss related matters.

4.1. "Complete" and "no risk trading"

Fig. 1 depicts the welfare obtained in the "complete" and "no risk trading" markets. Figures are in billions euro per year for a market of 110 TWh/yr.

Increased risk aversion decreases welfare (which is maximal with risk neutral agents). Also the difference of welfare between "complete" and "no risk trading" increases with risk aversion (the difference disappears for risk neutral agents).

It is important to point out that even if the market is complete the market outcome depends on the risk aversion of producer and consumer. Even after risk trading some risk remains (often called market risk in the context of the capital asset pricing model), see Ralph and Smeers (2015).

Fig. 2 reports investment in peak and base plants. Both decrease with risk aversion and the decrease is more significant in the absence of risk trading. These results are in line with intuition: the EOM defaults in presence of risk aversion, whether in terms of global welfare, peak and base investment. But complete risk trading corrects the situation. Because this is impossible to implement in the real world we examine partial completion of the risk market.

4.2. Yearly futures contracts

Consider a CfD on forward base load electricity price. We want to find the price and volume of the contract under different assumptions of market liquidity that we measure by a constraint on the ratio between traded volume and total electricity production (respectively infinite, 100% and 75%). A tight liquidity constraint implies a bid-ask spread (de Maere d′Aertrycke and Smeers, 2013 and Willems and Morbee, 2013)).

4.2.1. Welfare

Fig. 3 compares welfare of the three CfD markets to those of "complete" and "no trading". Welfare in a liquid CfD market comes close to the "complete" market. But this performance quickly degrades with illiquidity.

4.2.2. Investment

Investment in base plants increase above the "complete" level in a

[2] In the figures we report results for different degrees of risk aversion. For each calculation we take 10% expectation +90% CVaR. To vary the risk aversion we change the level at which the CVAR is taken (how many of the favourable scenarios are disregarded).

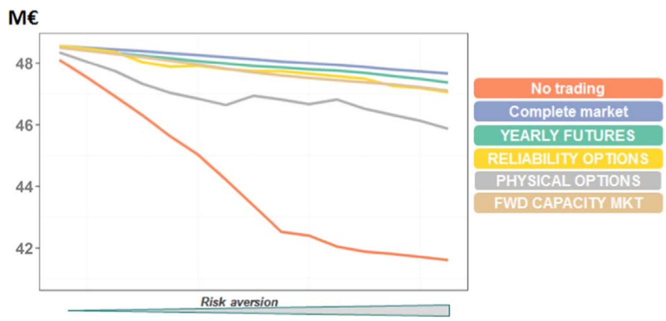

Fig. 11. Impact of the forward capacity market on the welfare as function of risk aversion.

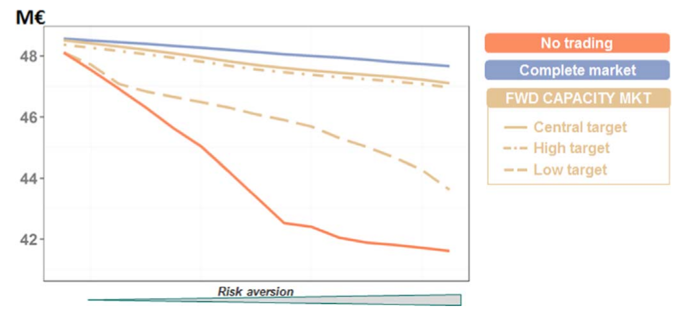

Fig. 13. Impact of the settings of the capacity demand curve on the welfare as a function of risk aversion.

liquid CfD market (Fig. 4) but are considerably lower and can even get close to the "no-trading level with illiquid CfDs. Peak investments lie between the two counterfactuals for the liquid market. Summing up a base load CfDs market corrects the impact of risk with a bias towards base plants. But the effect is quickly lost in an illiquid market. A CfD for peak electricity would obviously give different results.

4.2.3. Contract analysis

Assume mid risk aversion: the price of the CFD in a liquid market is 45 euros/Mwh, which is close to the full cost of 45.7 euros of the base plant (accounting for availability). The contract hedges 95% of the 110 k euro/MW CAPEX of the base plant. The relevant question is whether this contract can develop in real markets. The trading of that contract exceeds 150% of expected consumption. This is much higher than anything observed for (even short-term) electricity derivatives. A sufficiently liquid CfD market is thus unlikely to spontaneously develop. The result suggests an alternative: bilateral regulated contracts like the French Exeltium (www.exeltium.com/le-projet/) between large industrial consumers and EdF over a 24 year period at a price indexed to EdF costs or the UK example of public authorities offering a partial or total counterparty (for the nuclear development at Hinkley point) as substitutes for CfDs.

4.3. RO without physical back up

RO were suggested as market based remedies to the missing money (Vazquez et al., 2002, Oren, 2005 and other authors): generators sell options to consumers that then receive the right to buy electricity at a strike price lower than the VOLL. The contract protects the consumer and provides revenue to the generator for building peak generation units. ROs are measured in MW as physical generation capacity. Institutionally, regulators would initially introduce these contracts to launch the market that generators and consumers would later develop though new products of different strike prices. We first consider liquid ROs. We then explore a variant that imposes that RO be backed by

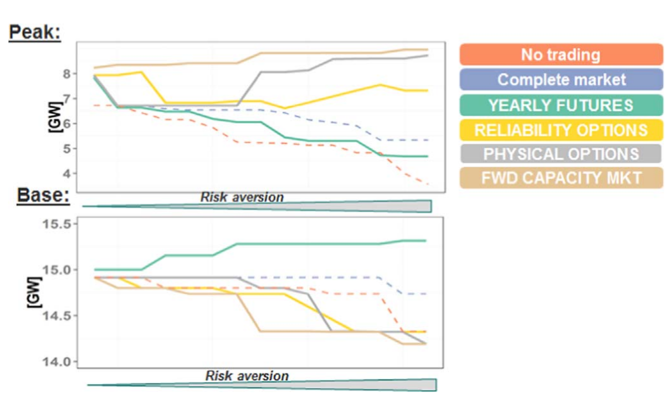

Fig. 12. Impact of the forward capacity market on the peak and the base capacities as function of risk aversion.

physical capacities. This latter proposal indirectly introduces illiquidity in the market.

4.3.1. Welfare

Fig. 5 compares the welfare obtained with ROs to "complete", "no risk trading" and CfD. Numerical tests were conducted with different strike prices but we only report the case of a strike price of 300 euros/MWh. Welfare increases close to the "complete" counterfactual but is slightly smaller than with CfDs. The performance of a RO obviously depends on the strike price: we report the best performance with respect to the "complete" counterfactual welfare but found that different strike prices between 100 and 300 euros/MWh had little impact.

As for the liquid CfD, trading figures shows that RO involves extensive trading that amount to 160% of the physical capacity. This is very high and unlikely to be found in any real market. As for CFDs but not reported here the efficiency of the contract decreases with the liquidity of the market. We later discuss the case where RO contracts must be backed by 100% physical capacity, which can be interpreted in terms of liquidity.

4.3.2. Investment

RO contracts incentivise investment in peak plants: they capture the willingness to pay to avoid scarcity and transfer it to investors that reduce that scarcity by investing. Fig. 6 shows that the contract effectively overshoots its objective and invests more than the "complete" market in peak units. This is compensated by underinvestment in base plants. Numerical tests show that the bias towards peak plants occurs for all strike prices (as expected) but that the over-investment depends on the case study and insufficient investments (compared to the complete market) are also possible.

4.3.3. Contract analysis

The price of the contract is 31 euro/kW. This compares to the 60 euro/kW capital cost of the peak plant and is thus lower than the investment cost. This illustrates the mechanism of the RO that covers investment cost by collecting both the price of the contract (31 euro/kW) and the gross margin equal to the strike price minus the operating cost. The latter contribution is the uncollected revenue in the missing money argument. As Hogan reserve pricing (Hogan, 2005) the RO introduces a source of revenue that is smoother than the occasional VOLL price.

4.4. RO with physical back up

Proponents of ROs recommend that each MW of option be backed by physical capacity: a generator cannot sell 100 MW of RO with only 50 MW of physical capacity. This condition can be implemented as strictly obligating physical capacity to be greater or equal to the amount of options or by a penalty when the option is in the money and the generator has insufficient capacity.

The back up requirement has several interesting aspects that we

Table 3
Decomposition of the producer's profit and implied hurdle rates Calibration: (0.1 expectation +0.9 CVaR @78% as risk measure) for the producer and the consumer.

	A- Investment cost *[k€]*	**B** – Expected gross profit from energy trading *[k€]*	**C**- Expected profit from financial trading *[k€]*	**D**- Risk premium *(B + C -A) /(A)*	**E**- Total Welfare *[k€]*
Complete market	2491	3245	−717	1.5%	48359
Yearly futures	2515	2941	−348	3.1%	48243
Illiquid Yearly futures	2460	3753	−964	13.4%	47870
Reliability options	2491	3066	−212	14.6%	47898
Physical options	2499	3061	245	32.3%	47324
Fwd capacity market – central	2591	1146	1549	4.0%	48192
Fwd capacity market - low	2580	2430	1392	48.1%	46835
Fwd capacity market - high	2732	1146	1690	3.8%	48051
No trading	2445	3838	0	57.0%	46301

only mention in passing. It has a moral hazard aspect: issuers must be physically credible. It also has a financial dimension: the back-up introduces a linkage between the physical and financial markets. We concentrate on the liquidity dimension: the back up limits RO trading. We discuss the case of a strict obligation on the physical back up (not selling more RO than the physically capacity) and briefly summarize the case of a penalty for insufficient back up generation capacity.

4.4.1. Welfare with strict obligation

Fig. 7 compares welfare (with the same 300/Mwh strike price as before) to previous results: the back up constraint clearly decreases the effectiveness of ROs.

4.4.2. Investment with strict obligation

Results without back up had shown that the volume of traded RO exceeds physical capacities. This implies that the back-up constraint creates an incentive to build capacity beyond the level obtained without back up in order to sell more options. This appears in Fig. 8. The model invests much more in the peak plant than in all other cases; there is a moderate decrease of base plants and the global result is an over-investment compared to "complete". This result is ambiguous though. Test with strike price between 100 and 300 euro/Mwh always show higher investment in peak units but global involvements can be higher or lower than in the pure RO case.

4.4.3. Penalty on lack of physical capacity

Consider now the case of a penalty imposed on the shortage between capacity and exercised options as was proposed in the UK reform. Fig. 9 reports welfare for tests conducted with penalties between euro 100 and 1000 per missing MW. Results are generally better than with the strict back up constraint but remain far from the welfare obtained without back up. The tendency to overbuild in order to sell options also appears here. Only very high penalties (higher than the VOLL) guarantee full back up. As with the physical constraint there is over investment in peak plants and ambiguous results on total capacity.

Table 5
Financial contract prices and benefits Calibration: (0.1 expectation +0.9 CVaR @78% as risk measure) for the producer and the consumer.

	Contract prices	***Risk premium***	***Trading gain for the producer [k€]***	***Trading gain for the consumer [k€]***
	[€/MWh]			
Yearly futures	45.8	−4.05%	1132	449
Illiquid Yearly futures	45.8 / 56.1	+6% / −13%	109	51
Realibility options	3.58	−12%	955	587
Physical options	5.34	25%	981	0

4.5. Forward capacity market (FCM)

FCM is the standard contender of EOM in discussions of adequacy (see de Vries 2007, de Vries and Heijnen, 2008 or Finon and Pignon, 2006). We take it here as a complement of EOM. Assume that the system operator requests capacity offers and sells capacity certificates to the owner of the capacity. In contrast with preceding contracts FCM does not offer risk-trading capabilities: the risk-taking consumers do not reveal their risk aversion but the government contracts capacity on their behalf.

The FCM clears in stage 0 and revenues to capacity accrue in stage 1. Determining the demand for capacity (whether through a demand function such as in Fig. 10 or a fixed value) is the controversial element of this instrument in US discussions. The EU concern is whether it

Table 4
Decomposition of the producer expected gross profit in expected infra-marginal rent and scarcity rent (with the associated number of scenario with scarcity).

	B – Expected gross profit from energy trading *(=B1+B2)*	**B1**- Expected infra marginal rent*[k€]*	**B2**- Expected scarcity rent *[k€]*	**E** - # Scenarios with scarcity
Complete market	3245	1051	2194	4/15
Yearly futures	2941	926	2015	4/15
Illiquid Yearly futures	3753	1001	2751	6/15
Realibility options	3066	1095	1971	4/15
Physical options	3061	1057	2005	4/15
Fwd capacity market - central	1146	1146	0	0/15
Fwd capacity market - low	2430	1083	1347	3/15
Fwd capacity market - high	1146	1146	0	0/15
No trading	3838	1088	2750	6/15

Calibration: (0.1 expectation +0.9 CVaR @78% as risk measure) for the producer and the consumer

Table 6
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the complete market case.

Complete [k€]	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	Risk- measure (0.1 Expectation +0.9 CVAR @78%)
A - Producer																
A1- Net profit from energy market	−923	7149	−966	−1431	−2101	7384	7131	−2110	−2080	−2091	−914	−960	−943	6252	−2091	−844
A2- Net profit from financial trading	1044	−7072	1044	1446	1984	−7072	−7072	1984	1984	1984	1044	1044	1044	−6131	1984	−1393
A3- Total net profit *(= A1+A2)*	121	77	77	15	−116	312	60	−125	−96	−107	130	83	101	121	−107	0
B- Consumer																
B1- Surplus from energy trading	48717	41403	49958	49722	49316	41948	42228	50935	50459	49033	51169	50282	48637	43107	51223	47081
B2- Net profit from financial trading *(=-A2)*	−1044	7072	−1044	−1446	−1984	7072	7072	−1984	−1984	−1984	−1044	−1044	−1044	6131	−1984	−852
B3- Total Surplus *(= B1+B2)*	47674	48475	48914	48276	47331	49019	49300	48951	48475	47049	50126	49239	47594	49239	49239	48359

Table 7
Net profit/surplus of the agent in the 15 scenarios for the energy markets (no financial market) and their risk evaluation in the no trading case.

No trading [k€]	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	Risk- measure (0.1 Expectation +0.9 CVAR @78%)
A - Producer																
Net profit from energy trading	−889	6971	344	−890	−2058	7193	6959	5770	−1780	−2048	−880	−926	−909	6083	−2048	0
B- Consumer																
Surplus from energy trading	48717	41403	48682	49215	49316	41948	42228	42957	50201	49033	51169	50282	48637	43107	51223	46301

disguises a State Aid element. We overlook this legal issue and focus on the impact of the specification of the demand for capacity. We examine three cases. The "central target" for capacity is correctly chosen ("optimized") by the regulator to foster investments that just cover the scenario with highest peak demand. The "low target" capacity is inferior by 10% to the maximal demand scenario for a price equal to the cost of peak capacity. This creates spike prices in some scenarios. The "high target" capacity is higher by 10% than the maximal demand at a price equal to the cost of peak capacity.

4.5.1. *Welfare and investment with a central target for capacity*

Fig. 11 compares the welfare in the central case to former results. Even though the FCM is not trading risk, it keeps customers away from price spikes, which implies that welfare is not dramatically affected compared to the market with CfDs and ROs. Capacities are depicted in Fig. 12; as expected one observes high peak and relatively low base investment.

4.5.2. *Welfare with different demand for capacity*

Fig. 13 compares the welfare obtained with the three different

Table 8
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the Yearly futures case.

Yearly futures [k€]	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	Risk- measure (0.1 Expectation +0.9 CVAR @78%)
A - Producer																
A1- Net profit from energy market	−922	3184	−966	−2126	−2118	7422	7175	−2127	−2097	−2109	−912	−959	−1226	6279	−2109	−1132
A2- Net profit from financial trading	689	−2841	689	2307	2307	−7223	−7223	2307	2307	2307	689	689	1082	−5605	2307	−1011
A3- Total net profit *(= A1+A2)*	−233	343	−277	181	189	199	−48	180	210	198	−223	−271	−144	675	199	0
B- Consumer																
B1- Surplus from energy trading	48717	45397	49958	50400	49316	41948	42228	50935	50459	49033	51169	50282	48921	43107	51223	47494
B2- Net profit from financial trading *(=-A2)*	−689	2841	−689	−2307	−2307	7223	7223	−2307	−2307	−2307	−689	−689	−1082	5605	−2307	−1160
B3- Total Surplus *(= B1+B2)*	48029	48238	49269	48093	47008	49171	49451	48628	48152	46726	50481	49594	47839	48712	48916	48243

Table 9
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the illiquid Yearly futures case.

Illiquid futures [k€]	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	Risk- measure (*0.1 Expectation +0.9 CVAR @78%*)
A - Producer																
A1- Net profit from energy market	−882	6754	509	−2075	−2067	7197	6972	5762	−2046	−2057	−873	−920	−902	6081	−2057	−109
A2- Net profit from financial trading	528	−5267	−547	1763	1763	−5511	−5511	−4276	1763	1763	528	528	528	−4276	1763	−1646
A3- Total net profit (*= A1+A2*)	−354	1487	−38	−312	−303	1686	1460	1487	−283	−294	−345	−392	−374	1805	−294	0
B - Consumer																
B1- Surplus from energy trading	48717	41629	48524	50400	49316	41948	42228	42957	50459	49033	51169	50282	48637	43107	51223	46409
A2- Net profit from financial trading (*=-A2+BID_ASK*)	−1938	3857	−864	−3173	−3173	4101	4101	2866	−3173	−3173	−1938	−1938	−1938	2866	−3173	−1540
A3- Total Surplus (*= B1+B2*)	46779	45486	47660	47227	46142	46049	46329	45823	47285	45860	49231	48344	46699	45973	48049	46460
C- Bid-ask spread																
C1- Total revenue from the bid-ask spread	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410	1410

target demands for capacity. As expected the low target does not perform well: there is no risk trading and little incentive to invest, therefore resulting in several scenarios where the electricity price reaches the cap. In contrast the central and high targets perform similarly and quite well compared to "complete". Results thus drastically depend on the regulated capacity target, which would impose to the regulator the task to optimize it to maximize welfare. Not shown here the low and high targets incentivise investment. As the central target, they overshoot the "complete" market for the peak plant and underinvest in the base plant. They largely correct the investment shortcoming of the "no risk trading" market.

5. Additional considerations

This section examines aspects not discussed before. It is conducted with a single risk measure (0.1 expectation +0.9 CVaR @78% as risk measure) for the producer and the consumer. The specific risk aversion is chosen to find a realistic risk premium for the complete market case with a Sharpe ratio of 0.22.

5.1. Implicit hurdle rates

Hurdle rates are key elements in investment projects. Table 3 show implicit risk premium and summary results for the different cases. These should be added to a 5% risk free rate rate used for computing annual capacity costs.

The first column recalls the case and the second gives the total "investment cost" or total assets (equities if assets are entirely financed by equity) of the generation system. Note that the examples only consider new capacities. "Investment cost" is reported together with total welfare (last column) to identify policies leading to excess infrastructure. The third and fourth columns report physical and financial trading in all cases except FCM (there is no risk trading in FCM) where the fourth column reports the capacity payment. The expected financial profit of the producer indicates the sign of the risk premium for the traded assets (yearly futures, reliability options and physical options). For this specific calibration, the risk premium is negative for yearly futures and reliability options but positive for physical options. Values are given in expectations as in standard investment theory (e.g. the CAPM) and are thus expected profit required by investors to compensate risk. The fifth column reports the implied risk premium. Risk premium added to the risk free rate (say 5%) gives the hurdle rate to screen investment proposals.

Table 4 reports the profits of the generators from physical trading; they are decomposed into infra-marginal profits and profits obtained when the price is at the cap. The latter column gives the number of demand scenarios when this occurs in some time blocs (reminder: a demand scenario contains three time blocs). Table 5 gives more information on the prices of the contracts.

Table 3 show a remarkable variety of implicit risk premium. This points to a very simple conclusion: market design is important for risk and risk should be part of any discussion of adequacy.

5.2. Further risks: unacceptable results in extreme events

Hurdle rates are expected return on investment. Tables 6–14 give additional information on these returns and investments. They list generators' gross margin and consumer's surplus for the different scenarios and their CVaRs. The first row gives the column names (scenario number or CVaR). The second and third rows report the profits accruing to generators from physical and financial trades respectively, with the fourth row giving their sum or net value (note that CVaR are not additive and hence the sum of the CVaR of physical and financial trades in the last column is not equal to the CVaR of the sum). The next rows of the table give the same information for consumers' surplus.

Table 10
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the FInancial realiability option case.

Options financial [k€]	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*	*#13*	*#14*	*#15*	**Risk- measure** *(0.1 Expectation +0.9 CVAR @78%)*
A - Producer																
A1- Net profit from energy market	−934	3744	−977	−935	−2103	7418	7157	−2112	−1880	−2094	−925	−971	−954	6286	−2093	−955
A2- Net profit from financial trading	1499	883	1499	1499	1499	−6853	−6853	1499	1499	1499	1499	1499	1499	−6853	1499	−640
A3- Total net profit *(= A1+A2)*	565	4627	522	564	−604	565	303	−613	−381	−595	574	528	545	−567	−594	0
B- Consumer																
B1- Surplus from energy trading	48717	44837	49958	49215	49316	41948	42228	50935	50257	49033	51169	50282	48637	43107	51223	47311
B2- Net profit from financial trading *(=-A2)*	−1499	−883	−1499	−1499	−1499	6853	6853	−1499	−1499	−1499	−1499	−1499	−1499	6853	−1499	−1293
B3- Total Surplus *(= B1+B2)*	47218	43954	48459	47716	47816	48801	49082	49436	48758	47534	49670	48783	47138	49961	49724	47898

Table 11
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the Physical realiability option case.

Options physical [k€]	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*	*#13*	*#14*	*#15*	**Risk- measure** *(0.1 Expectation +0.9 CVAR @78%)*
A - Producer																
A1- Net profit from energy market	−930	4250	−973	−1427	−2108	7419	7163	−2117	−2087	−2099	−921	−967	−950	6284	−2098	−981
A2- Net profit from financial trading	1223	266	1223	1223	1223	−3351	−3351	1223	1223	1223	1223	1223	1223	−3351	1223	0
A3- Total net profit *(= A1+A2)*	293	4516	250	−203	−884	4069	3812	−894	−864	−875	303	256	273	2933	−875	0
B- Consumer																
B1- Surplus from energy trading	48717	44335	49958	49711	49316	41948	42228	50935	50459	49033	51169	50282	48637	43107	51223	47324
B2- Net profit from financial trading *(=-A2)*	−1223	−266	−1223	−1223	−1223	3351	3351	−1223	−1223	−1223	−1223	−1223	−1223	3351	−1223	−1071
B3- Total Surplus *(= B1+B2)*	47494	44069	48735	48487	48092	45298	45579	49712	49236	47810	49946	49059	47414	46458	50000	47324

Table 12
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the Fwd capacity market central demand for capacity.

Fwd capacity market - central [k€]	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*	*#13*	*#14*	*#15*	**Risk- measure** *(0.1 Expectation +0.9 CVAR @78%)*
A - Producer																
A1- Net profit from energy market	−1035	−1080	−1078	−1036	−2203	−1072	−1020	−2213	−1215	−2194	−1026	−1072	−1055	−2191	−2195	−1545
A2- Net profit from capacity market	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549	1549
A3- Total net profit *(= A1+A2)*	514	469	471	513	−654	477	529	−664	334	−645	523	477	494	−642	−645	0
B- Consumer																
B1- Surplus from energy trading	48718	49560	49958	49215	49316	50857	50764	50935	49491	49033	51170	50282	48637	51932	51223	49741
B2- Net profit from capacity market *(=-A2)*	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549	−1549
B3- Total Surplus *(= B1+B2)*	47168	48011	48409	47666	47767	49308	49215	49386	47942	47484	49620	48733	47088	50383	49674	48192

Table 13
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the Fwd capacity market low demand for capacity.

Fwd Capacity market - low [k€]	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	**Risk- measure** *(0.1 Expectation +0.9 CVAR @78%)*
A – Producer																
A1- Net profit from energy market	−1012	−1056	−1055	−1108	−2189	7824	7518	−2198	−2169	−2180	−1002	−1049	−1031	635	−2180	−1392
A2- Net profit from capacity market	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392	1392
A3- Total net profit *(= A1+A2)*	380	335	337	284	−797	9216	8910	−806	−777	−788	390	343	361	2027	−788	0
B- Consumer																
B1- Surplus from energy trading	48717	49560	49958	49311	49316	41948	42228	50935	50459	49033	51169	50282	48637	49121	51223	48227
B2- Net profit from capacity market *(=-A2)*	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392	−1392
B3- Total Surplus *(= B1+B2)*	47326	48168	48566	47919	47924	40556	40836	49544	49067	47641	49777	48890	47245	47729	49831	46835

A quick observation of the gross margins and losses shows that they can reach extremely high values. The situation is smooth in Table 6 but extremely chaotic in Table 7 (which only refers to physical trading since there is no financial trading in "no risk trading"). The hurdle rate of 57% is unrealistically high and can only happen with a large expected number of hours with electricity price at the CAP. As Table 4 indicates this occurs in 6 out of the 15 demand scenarios. Gross margin are then very volatile with high gains and also large losses. Regulators will certainly object to net returns of the order of 290% (7193 in scenario 6 for asset value of 2445) and take actions. The inability of the policy maker to commit not to expropriate high returns (*ex*-post) will hence lead to underinvestment. (This inability has been studied in the context of short term contracts and is known as the "Ratchet effect", Laffont and Tirole, 1998). This risk is not included in the analysis.

Large losses can also occur in some scenarios, some leading the generator close to bankruptcy (scenario 5 where losses of 2058 almost wipe out the 2445 assets). This creates a true liquidity risk, which the model also reveals.

5.3. Liquidity risk

The liquid CfD offers a strong incentive to invest. But illiquidity deteriorates its effectiveness. Table 1 shows a risk premium of 13.4% for the illiquid CfD compared to the 3.1% of the liquid CfD. This is accompanied by volatile profits and losses as in "no risk trading" (see Table 6 for numerical details with profits in some scenarios reaching 73%). One cannot predict the liquidity of new markets such as CfD or RO. These markets are thus affected by a true liquidity risk that the model does not assess but can help pinpoint.

5.4. Regulatory risks

Results of the FCM case show that the choice of that demand curve may drastically impact the result of the market. Specifically FCM gives very asymmetric results depending on whether one underestimate or overestimate the capacity target. But the choice of the FCM is the responsibility of the regulator or system operator and hence another regulatory risk. Last the back up requirement on RO is another regulatory risk with serious consequences.

6. Conclusion and policy implications

Risk and long-term contracts are often mentioned in discussion of investment in the energy transition of the restructured power sector but rarely analysed quantitatively. This paper offers some treatment of those instruments that it also compares to more traditional policies such as Forward Capacity Market (FCM) where the system operator signs contracts based on his view of what the consumers need. The analysis always considers these instruments as additions and not substitutes to energy only markets (EOM).

The impact of risk depends not only on its extent and the market risk aversion but also on how it can be mitigated by trading among agents. We first test the impact of risk aversion on investment through two extreme counterfactuals of risk trading ("complete" and "no risk trading"). We find that risk, risk aversion and the extent of risk trading drastically impact investment in EOM. This justifies exploring the domain between these two extremes by introducing contracts suggested in different policy proposals.

We concentrate on Contracts for Differences (CfD) and Reliability Options (RO) that are reference instruments proposed to foster investment in the restructured power sector. We find that these contracts are quite effective complements to EOM. We also find that adding an FCM to the EOM can have quite different effects depending on how the demand for capacity is calibrated. A bad calibration entails significant loss of investment and welfare.

But these instruments bring their own risk. We find that both the

Table 14
Net profit/surplus of the agent in the 15 scenarios for the different markets (energy and financial) and their risk evaluation in the Fwd capacity market high demand for capacity.

Fwd capacity market - high [k€]	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*	*#13*	*#14*	*#15*	**Risk- measure** *(0.1 Expectation +0.9 CVAR @78%)*
A - Producer																
A1- Net profit from energy market	−1175	−1220	−1218	−1176	−2344	−1212	−1160	−2353	−1356	−2335	−1166	−1212	−1195	−2331	−2335	−1690
A2- Net profit from capacity market	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690	1690
A3- Total net profit *(= A1+A2)*	515	470	472	514	−654	478	530	−663	334	−645	524	478	495	−641	−645	0
B- Consumer																
B1- Surplus from energy trading	48717	49560	49958	49215	49316	50857	50764	50935	49491	49033	51169	50282	48637	51932	51223	49741
B2- Net profit from capacity market *(=-A2)*	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690	−1690
B3- Total Surplus *(= B1+B2)*	47027	47870	48268	47525	47626	49167	49074	49245	47801	47343	49479	48592	46947	50242	49533	48051

CfD and RO may require trade volumes never encountered so far in power markets. Lack of liquidity can affect any financial market (and have devastating results as the protracted financial crisis shows). Regulation and its unintended consequences can also create liquidity risk. We illustrate their impact by exogenously assuming insufficient liquidity of the CfD market and regulatory moves that hampers liquidity in the RO market. Both significantly degrade the efficiently of the instruments.

All this suggests having public authorities intervene in some contracts that are relatively easy to regulate (see for example Moreno et al, 2010). CfD seem simpler than RO for that purpose. This may also create issue as a public authority setting a target for contracting (or a hedging obligation) may effectively be seen as introducing a capacity market. In any case having Public authorities, as counterparties would also force them to better assess what they are sometimes asking.

This discussion can be rephrased in the more common terms of hurdle rates. Long term contracts in liquid markets and very well calibrated FCM are very effective in reducing hurdle rates and hence favour investment. But contracts are vulnerable to liquidity and FCM to calibration. All the mechanisms are originally designed to solve the missing money problem and are extensively analysed for a deterministic setting. In our stochastic setting, it turns out that different proposals perform very differently and might even fail to provide a much improved outcome (as long as liquidity might not be there).

This leads to a very simple policy implication: risk can seriously damage the effect of remedies to insufficient investment. The deterministic and complete risky markets are non-ambiguous paradigms that lead to clearly defined analysis. Incomplete markets form a whole spectrum of situations that each needs to be studied individually, most often by numerical simulations. It is thus of the essence not to unnecessarily add risk. Some risk is exogenous and unavoidable. Other is internally generated by the policy and should be avoided. Compensating for this risk by trading is difficult and may not give the intended effects. One should also be wary of measures that "boost" some instrument without a full argumentation of their efficiency. Also measures may be difficult to calibrate.

This work is only illustrative in the sense that the representation of the power sector is simplified; but the simulations show that even simple models can give quite contrasted results of a type not often discussed so far. Further numerical investigations that extend the model representing the financing options and constraints (a mix of bonds and equities) should deepen the analysis.

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