El desafío de la implementación de los mecanismos para la internalización de los "costos no convexos"

Capítulo 3: La mirada desde la planificación y operación del sistema eléctrico

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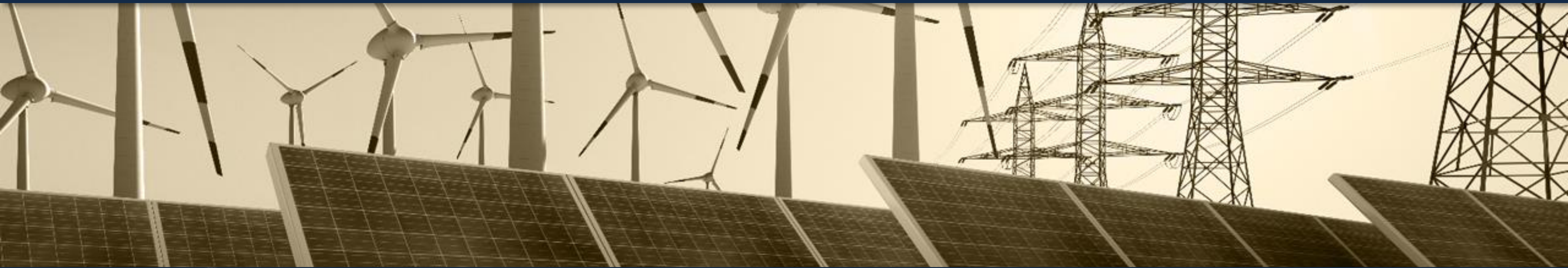

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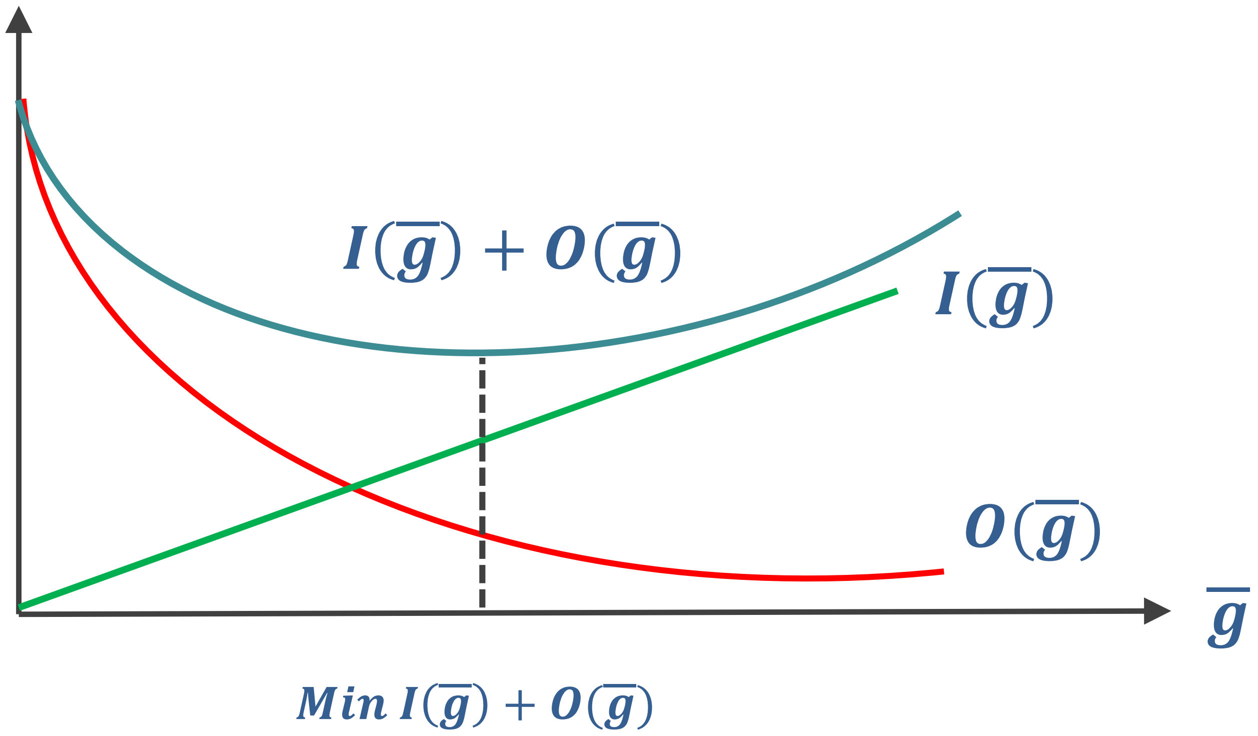
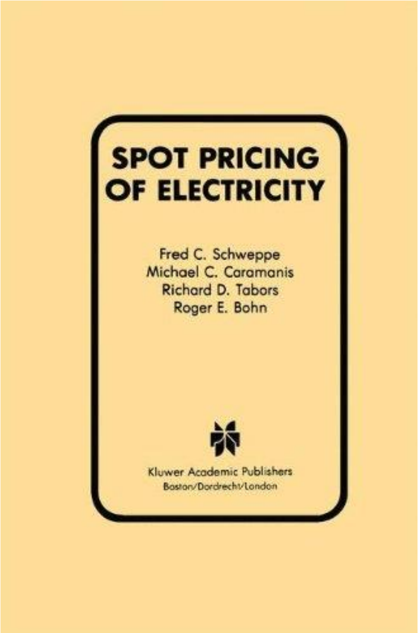
Centralized expansion planning



- Historically, power systems were centrally planned and operated by government agencies and verticalized utilities with regulated tariffs
- The main reason for not relying on market mechanism was the *economies of scale* of hydroelectric and thermal generation projects
  - A 1,000 MW plant was cheaper, on a US$/MWh basis, than 10 plants rated 100 MW each

Power market reform components

- *Development of gas-fired combined cycle plants*, which were economically competitive and did not have significant economies of scale
- *Successful deregulation of the telecon industry*, which served as an example to be followed by the electricity industry
- The book *Spot Pricing of Electricity* provided a conceptual framework for electricity market design: electric energy must be treated as a commodity which can be bought, sold, and traded, considering its time- and space-varying values and costs
- The *hourly spot price* is the basis of the energy marketplace because it provides the foundation for all transactions



Spot prices

- The spot price corresponds to the *system marginal cost*, i.e. the cost of providing an additional MWh of demand
- Example: thermal plants with given unit operation costs ($/MWh). Dispatch generators by increasing costs (merit-order dispatch) until the hourly load is met. The spot price is the operating cost of the generator loaded last (marginal generator)

$$z = \ Min \sum_{j=1}^{J} c_j \times g_j$$

$$\sum_{j=1}^{J} g_j = d \quad \pi_d \ \leftarrow \text{dual variable}$$

$$g_j \leq \overline{g}_j$$

The dual variable π_d is the derivative of the optimal operation cost z with respect to a marginal change in the demand d. Therefore, it corresponds to the system marginal cost (spot price)

Economic signals for expansion

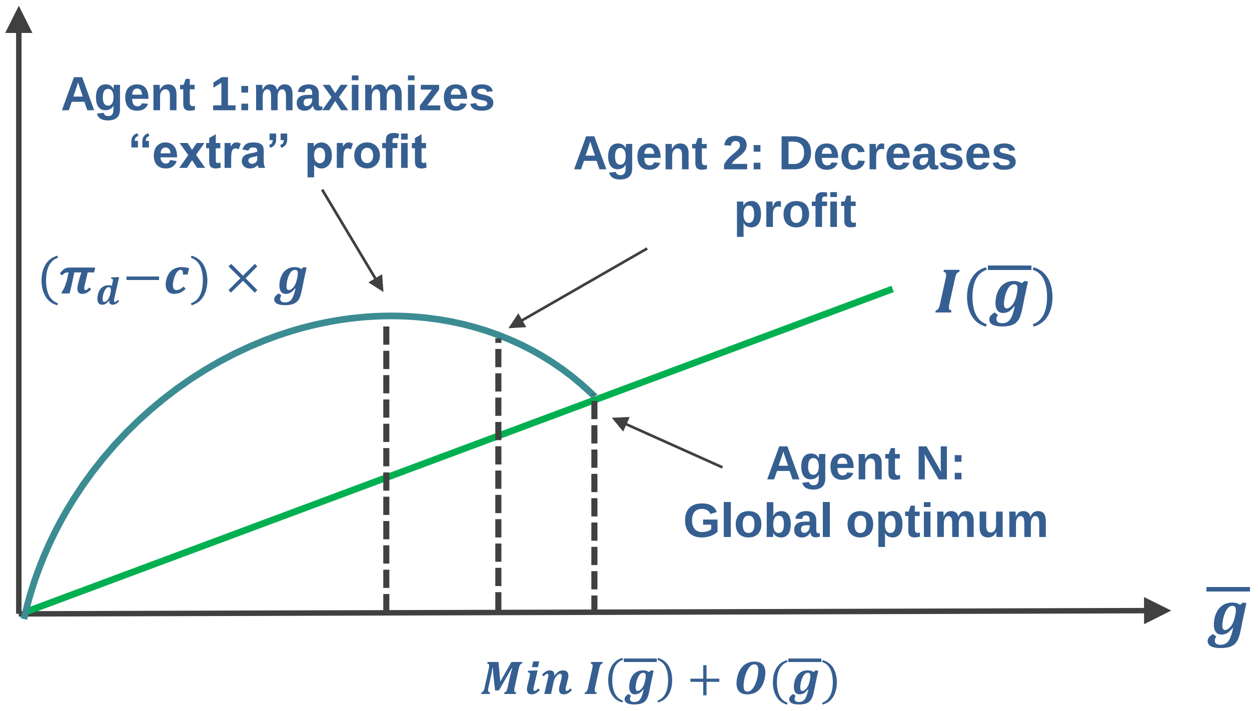
$$z = \ Min \sum_{j=1}^{J} c_j \times g_j$$

$$\sum_{j=1}^{J} g_j = d \qquad \pi_d \ \leftarrow \text{spot price}$$

$$g_j \leq \overline{g}_j \qquad\qquad \pi_{\overline{g}_j} \leftarrow \text{capacity marginal cost}$$

- The dual variables $\{\pi_{\overline{g}_j}\}$ are derivatives of z with respect to increases in generation capacities $\{\overline{g}_j\}$
- $\pi_{\overline{g}_j} = (\pi_d - c_j) \times g_j$ (net spot revenue)
- If the investment cost I_j of an increment in $\overline{g}_j$ is smaller than the corresponding decrease in operating costs, given by $\pi_{\overline{g}_j}$, then it is economically beneficial to reinforce the capacity; otherwise, the reinforcement should not be carried out $\Rightarrow$ $\boldsymbol{-\pi_{\overline{g}_j} \geq I_j}$

Spot price-based optimal expansion



- A key demonstration of the *Spot Pricing* book was that, if there is no market power, *the spot market scheme will induce the least-cost expansion*, i.e. the same expansion that would be obtained by a perfect centralized planning scheme. In other words, *spot price signals are economically efficient*
- Given that centralized planning results were disappointing in many countries due to political interference, inefficient management of state-controlled agencies and other factors, a market-based scheme that was demonstrably efficient attracted great interest

The Primal-Dual Equality is at the core of the demonstration

$$\sum_{j=1}^{J} c_j \times g_j = \pi_d \times d + \sum_{j=1}^{J} \pi_{\overline{g}_j} \times \overline{g}_j$$

- Rearranging terms and replacing d by $\sum_{j=1}^{J} g_j$

$$\pi_d \times (\sum_{j=1}^{J} g_j) = \sum_{j=1}^{J} c_j \times g_j - \sum_{j=1}^{J} \pi_{\overline{g}_j} \times \overline{g}_j$$

- Remembering that $-\pi_{\overline{g}_j} \geq I_j$, the expression becomes:

$$\pi_d \times g_j \geq c_j g_j + I_j \times \overline{g}_j \text{ for } j = 1, \dots, J$$

The spot revenue of a generator should cover (or exceed) its operation cost plus its investment cost

Nonconvex operating problems (MIP formulation)

$$z = Min \sum_{j=1}^{J} \delta_j \times y_j + \sum_{j=1}^{J} c_j \times g_j$$

$$\sum_{j=1}^{J} g_j = d$$

$$g_j - \overline{g}_j \times y_j \leq 0$$

$$g_j - \underline{g}_j \times y_j \geq 0$$

y_j binary variable that represents the unit commitment decision

δ_j unit commitment cost

$\underline{g}_j$ minimum generation when plant *j* is committed

Differently from the LP formulation, there are no dual variables associated to the constraints of a MIP problem, nor a primal-dual equality. Therefore, it becomes necessary to create an approximation to the spot price

Approximation: fix the binary variables and solve an LP

$$\tilde{z} = Min \sum_{j=1}^{J} c_j g_j$$

$$\sum_{j=1}^{J} g_j = d \quad \leftarrow \quad \tilde{\pi}_d$$

$$g_j \leq \overline{g}_j \times y_j^* \quad \leftarrow \quad \tilde{\pi}_{\overline{g}_j}$$

$$g_j \geq \underline{g}_j \times y_j^* \quad \leftarrow \quad \tilde{\pi}_{\underline{g}_j}$$

- Problem: spot revenues $\tilde{\pi}_d \times g_j$ *don't ensure recovery of operation costs*
- *Duality gap*: shortfall between spot revenues and operating costs

Objective of this study: how to "close" the duality gap

Variable renewable energy (VRE) sources and the duality gap

- VRE sources such as solar and wind have significant economic and environmental upsides; however, they require additional generation reserves to handle their intermittency
- The previous AG study showed that the increase in VRE penetration led to an increase in unit commitment frequency $\Rightarrow$ higher flexibility costs $\Rightarrow$ higher duality gaps
- Additional factors that increase the duality gap:
  - VRE sources tend to decrease spot prices (at the extreme, zero) $\Rightarrow$ smaller spot revenues
  - The dynamic probabilistic reserve (DPR) is applied as a *constraint* to the short-term dispatch; however, the correct modeling is a co-optimization of dispatch costs and reserves. Using DPR as a constraint lower spot prices $\Rightarrow$ duality gap increases

Alternatives for "closing" the duality gap

1. "*side payment*": Calculate for each generator the shortfall between spot revenues and operating cost. The total shortfall then charged to the load
2. *Adjust spot prices* (in practice, increase them) to ensure that the generators' spot price revenues cover their operation cost.

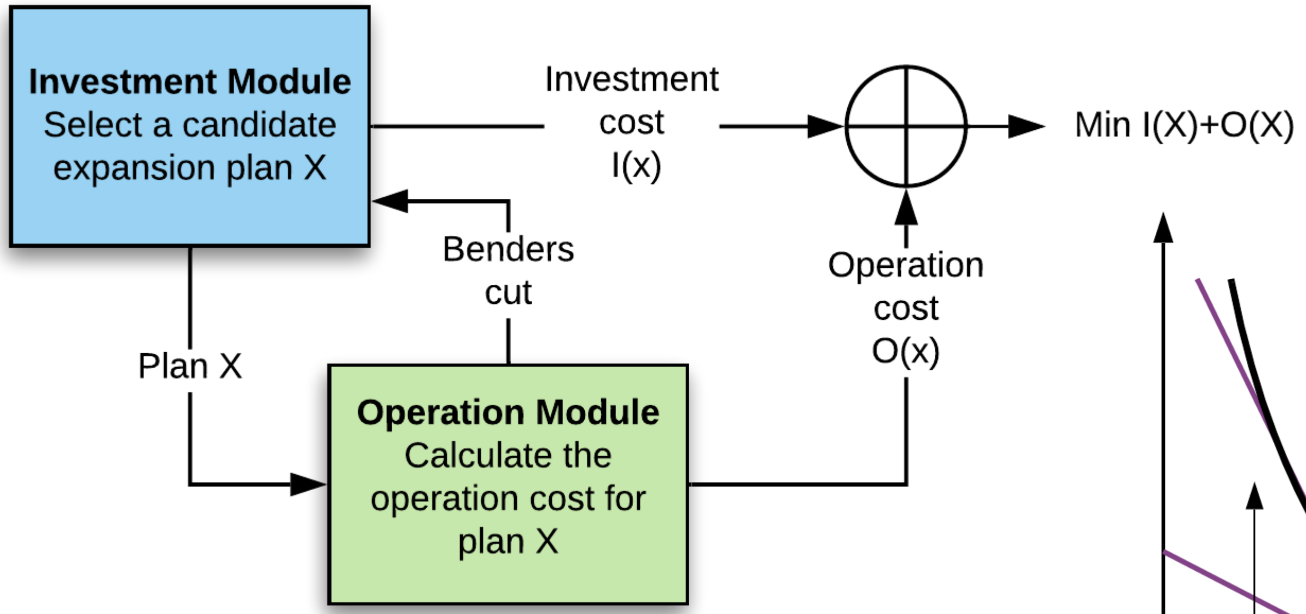
It is important to observe that both alternatives are "wrong", in the sense that they do not ensure the pricing efficiency of the convex spot pricing theory

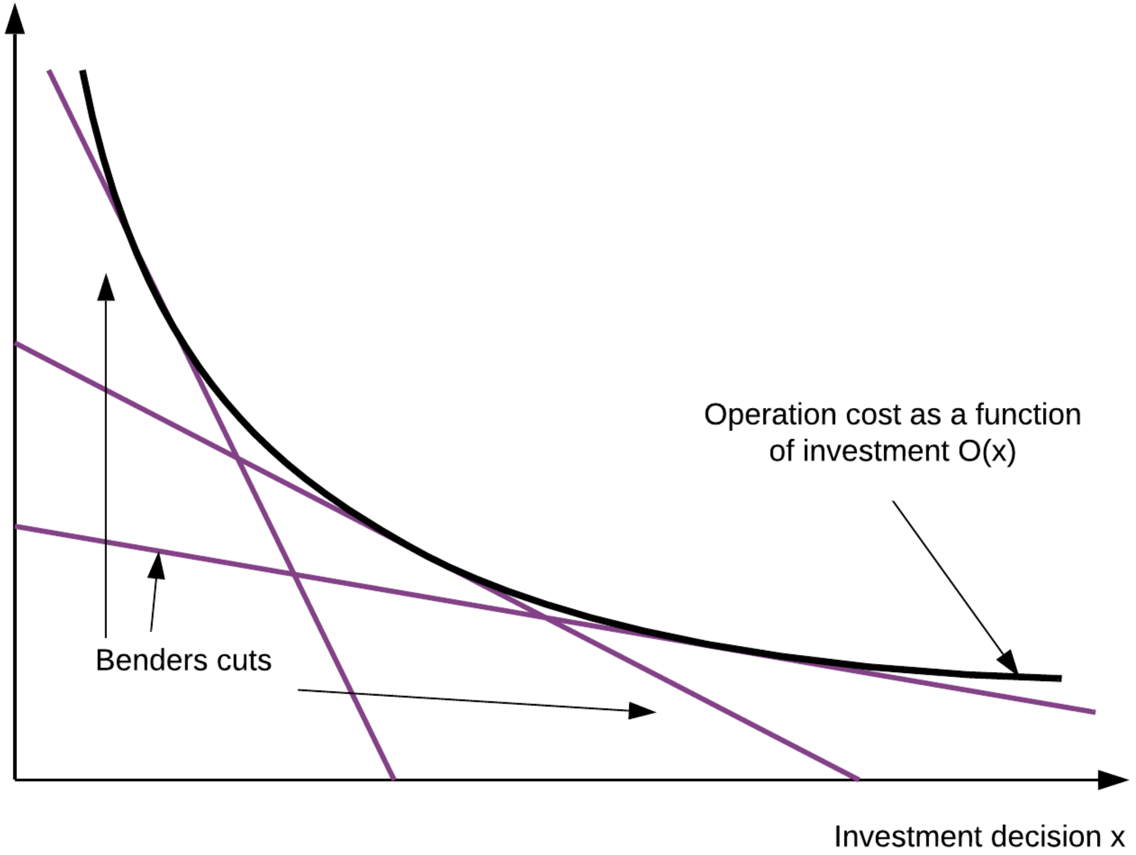
The question is then: which approach is "less wrong" than the other

Ideal Assessment Scheme

- Determine the system expansion that would result from the two alternative spot market modifications, "side payments" and "spot price adjustment" and calculate the corresponding *average cost to consumers* (ACC), in $/MWh
  - Side payments: ACC = (total spot payment + side payments ($)) ÷ total load (MWh)
  - Spot price adjustments: ACC = total spot payment ÷ total load

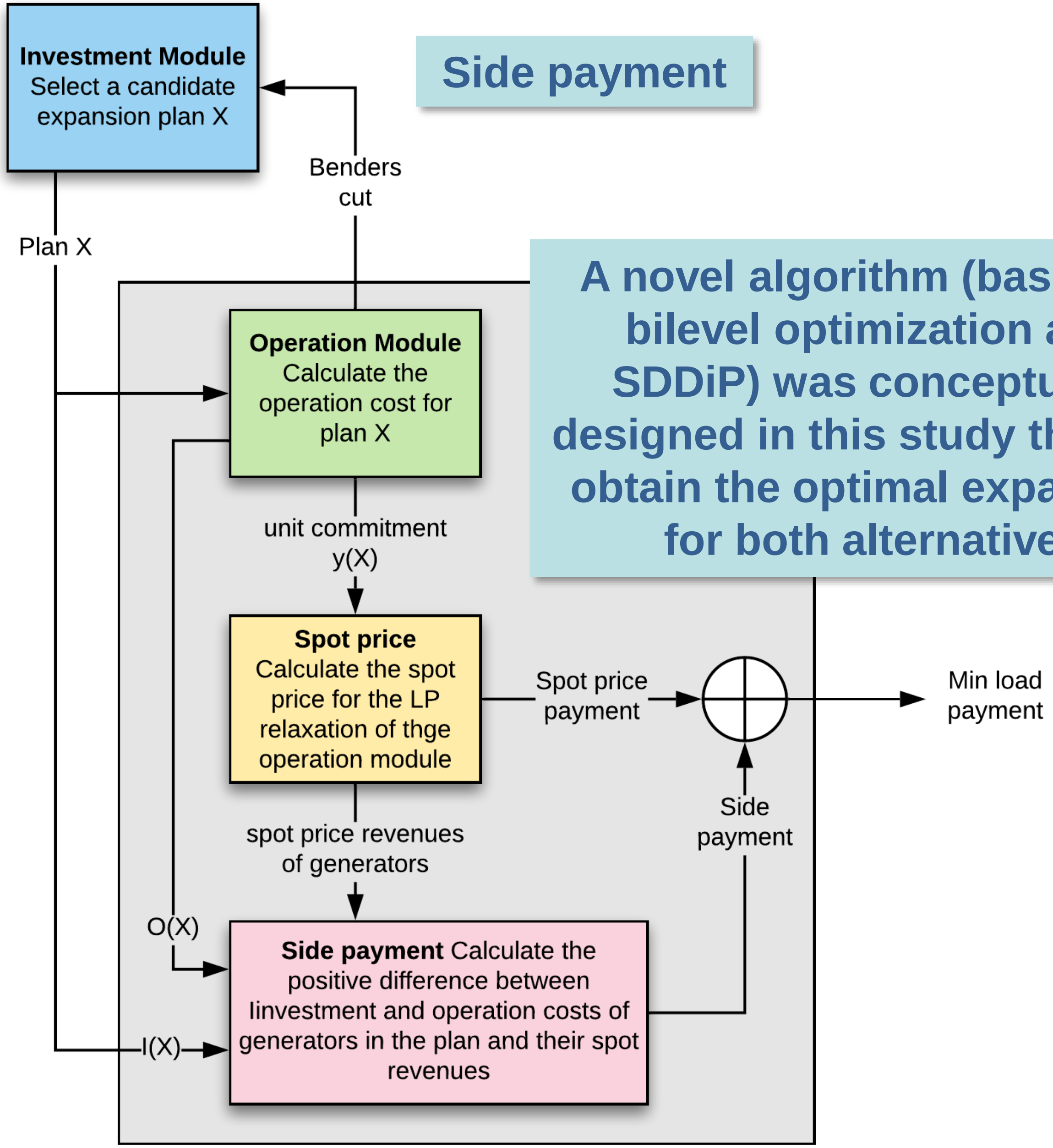
Algorithm for centralized planning (reference)





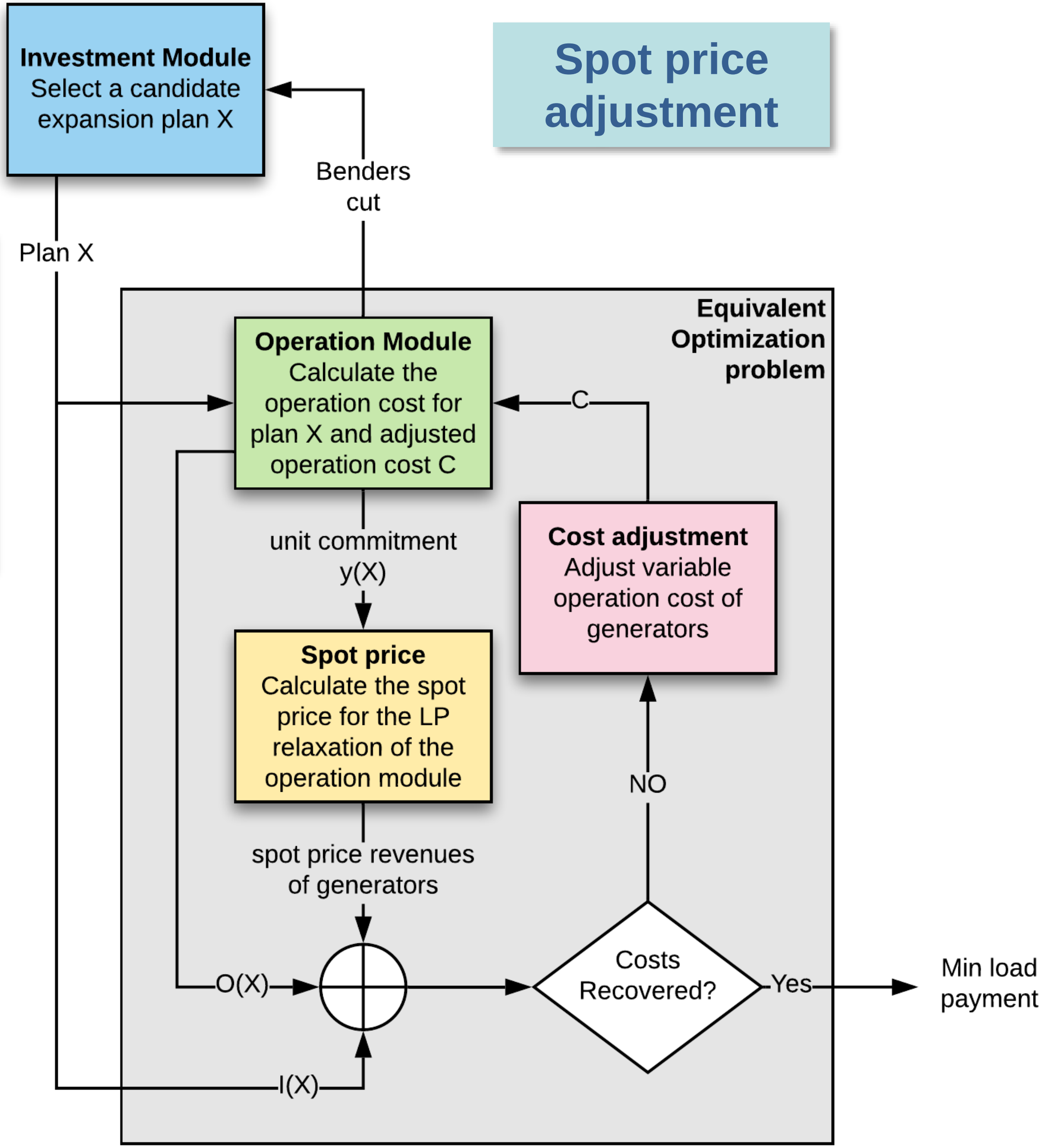
Historically, the Benders decomposition scheme required convexity in the operation problem O(x).
The recent SDDiP algorithm produces optimal Benders cuts for nonconvex operation problems (binary decisions x)

Side payment



A novel algorithm (based on bilevel optimization and SDDiP) was conceptually designed in this study that can obtain the optimal expansion for both alternatives

Spot price adjustment



Approximate scheme

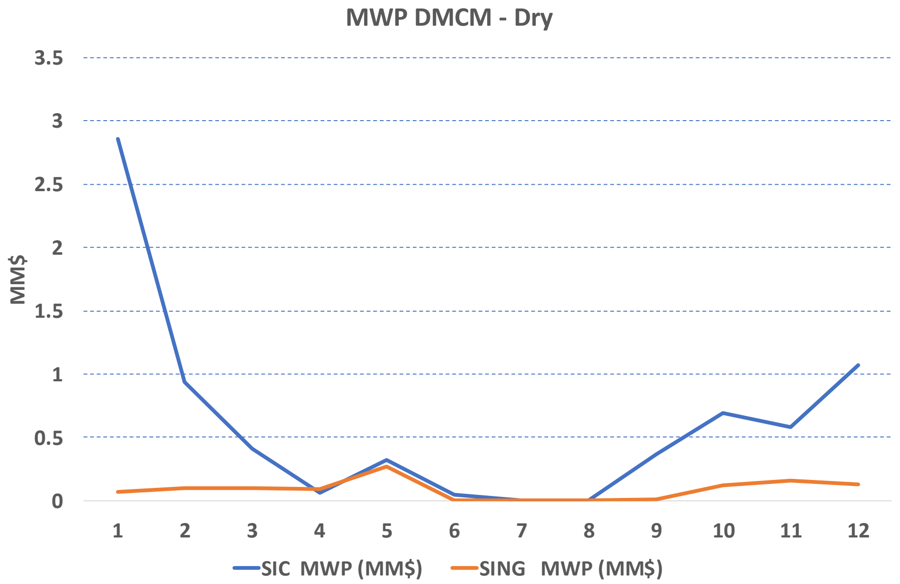
- The implementation of the new algorithm is complex and cannot be carried out within the limited time for this project. For this reason, the following approximation was used:

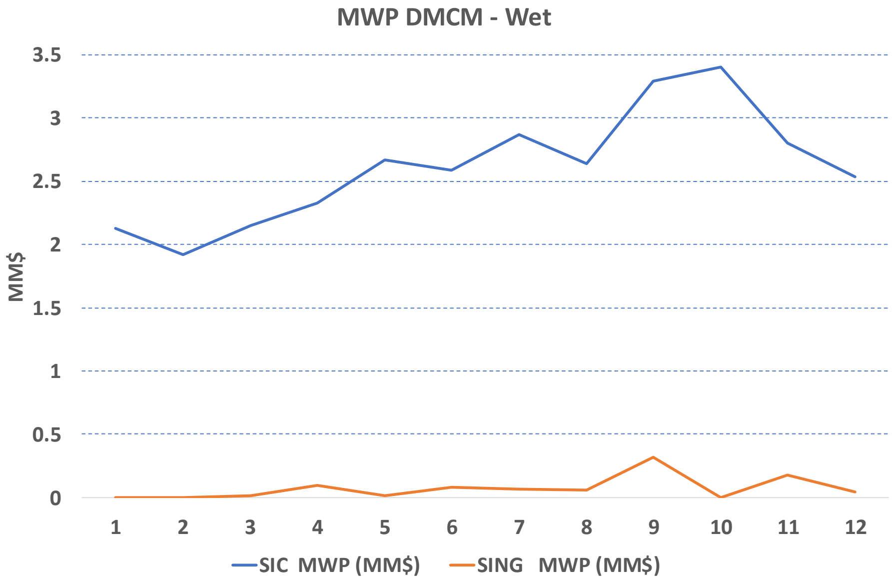
1. Assume that in both cases the system expansion is the one obtained by a "perfect" centralized optimization algorithm;
2. Carry out a probabilistic hourly simulation of system operation and calculate the duality gaps for all generators;
3. "Close" the duality gaps using the "side payment" and "spot adjustment" alternatives and calculate the ACC for both cases;
4. The "least bad" option would be the one with the lowest cost to the consumer

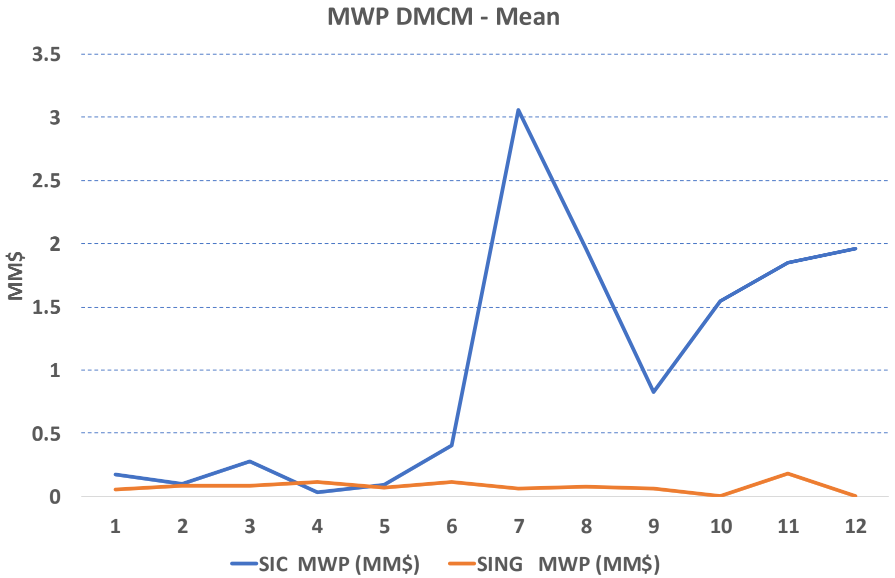
Study results

- System configuration from the previous AG study, year 2030
- Monthly optimal operation with hourly resolution (MIP problem)
- Spot prices calculated by fixing binary variables and solving LP
- Side payment: for each generator, net shortfall between spot revenue and operation cost along the month
- Spot price adjustment: Max (spot price, Max $\left\{\frac{\delta_j + c_j \times g_j}{g_j}\right\}$)

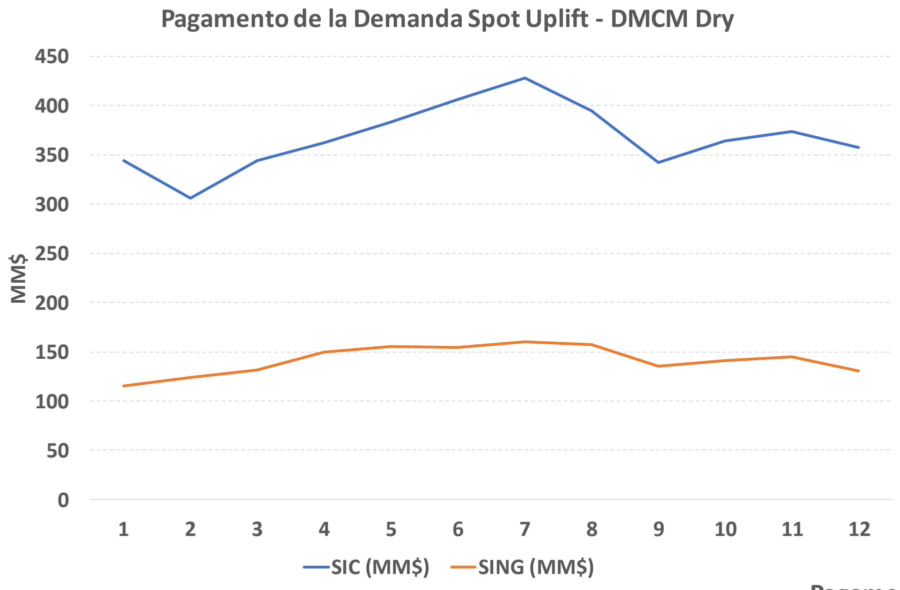
Side payments (million US$)

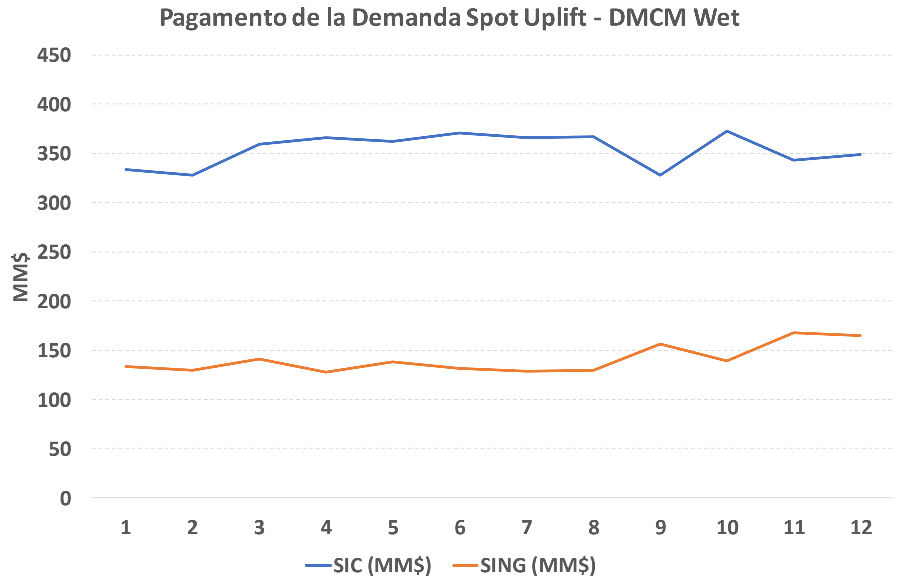


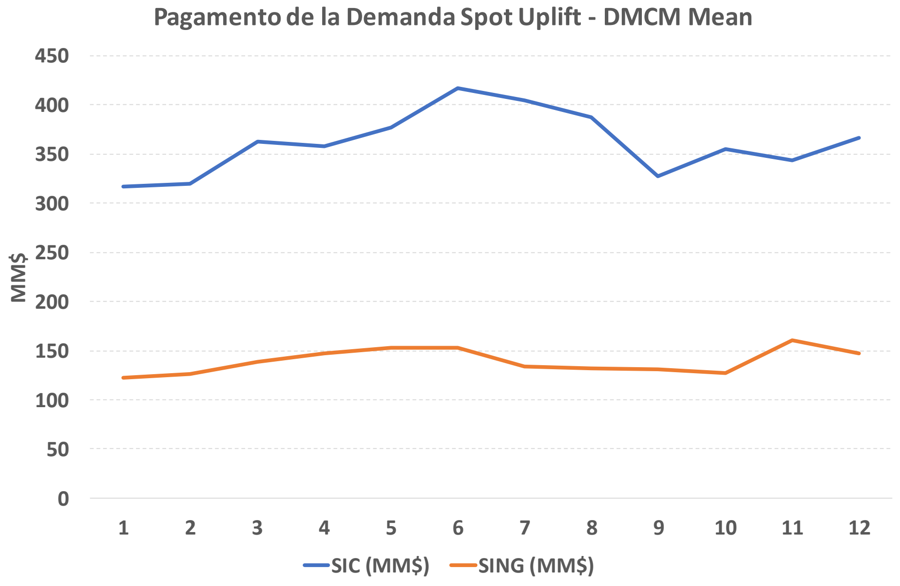




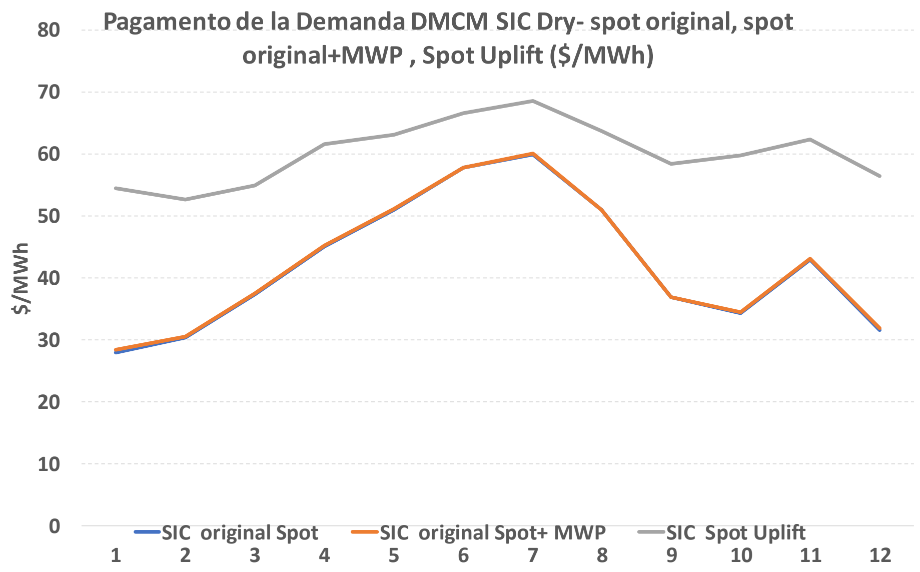
Spot price adjustment (million US$)

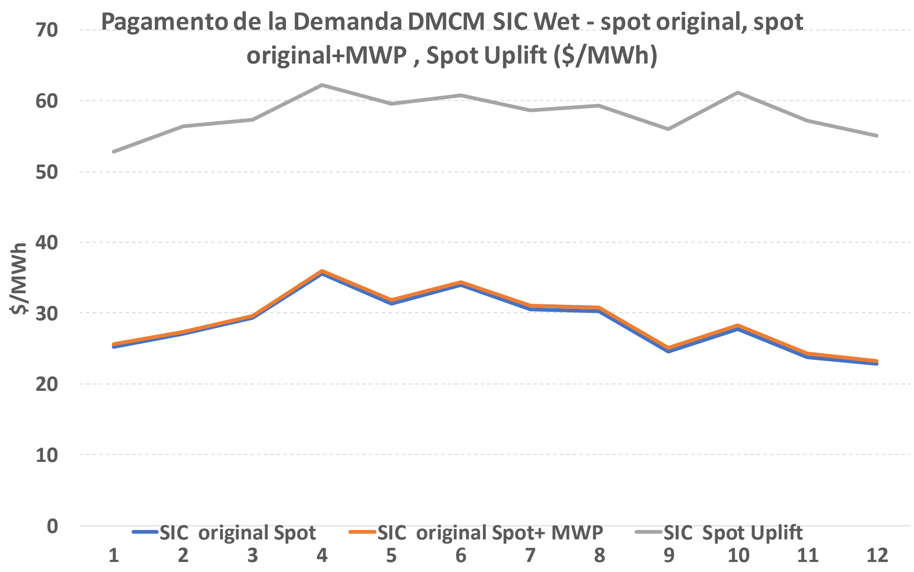


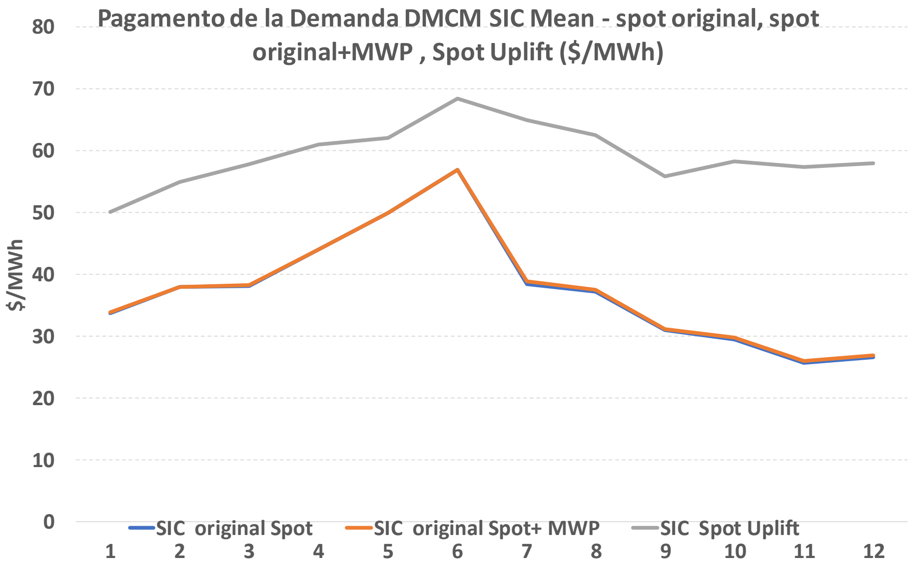




Average cost to consumers (ACC) ($/MWh) - SIC

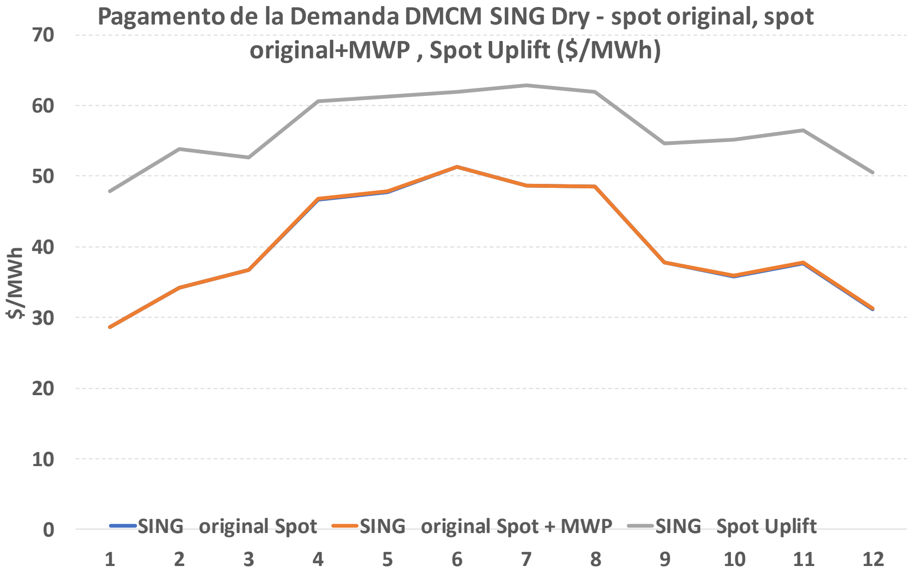


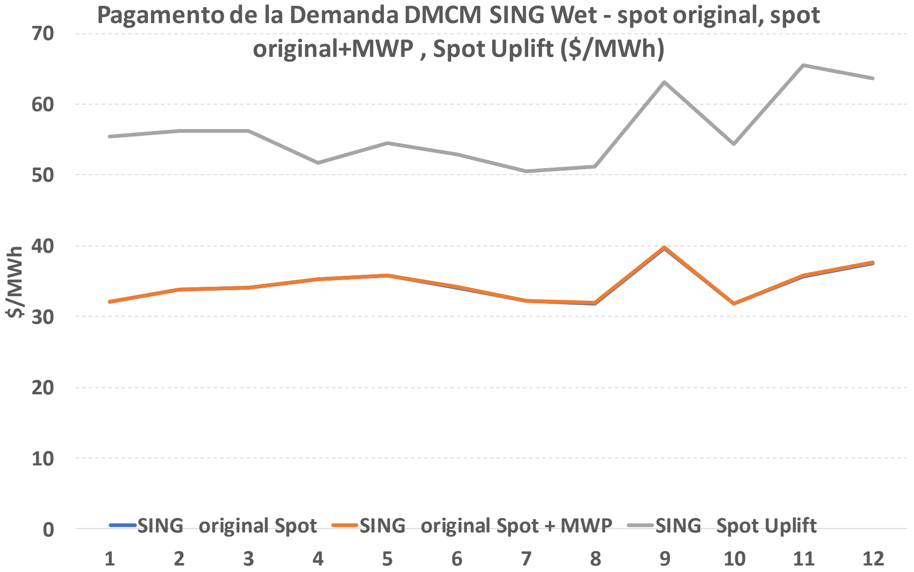


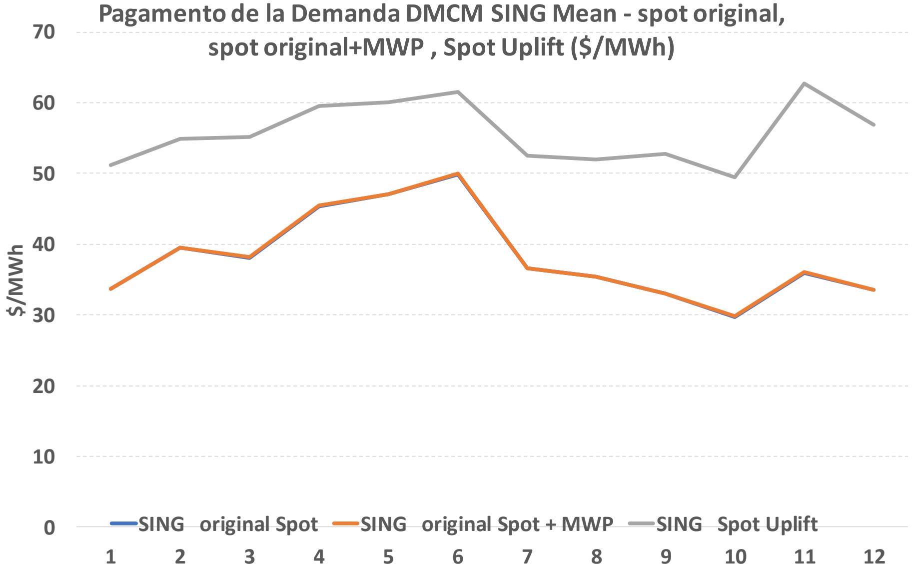


ACC with spot adjustment is 60% higher than ACC with side payments

Resultados – Comparación del pagamento de la demanda DMCM SING ($/MWh)







ACC with spot adjustment is 50% higher than ACC with side payments

Analysis of results

- The results indicate that spot price adjustments would lead to costs to consumers that are substantially higher than the side payment alternative.
  - The main reason: the increased spot price remunerates all generators, not only those with operating cost shortfalls.
  - Another factor is that the side payment scheme can be applied to the *net shortfall* between spot revenues and operation along a given period. In contrast, the "netting" in the case of spot price adjustment is limited to the accounting and clearing cycle of wholesale energy market.
- Another consequence of the "extra" spot remuneration for VRE resources is that a "*duality gap spiral*" could occur:

Increased VREs → increased reserve → increased commitments and lower spot prices → higher duality gaps → higher spot price adjustments → increased VREs, and so on …