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Maximising profits through efficient pulse load operation

A novel look at the dilemma of flexibility versus baseload efficiency in the demanding load conditions of the RES-heavy power systems of the 21st century

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1. Abstract

The share of wind and solar power in many grids has grown rapidly, making it increasingly difficult to stabilise the supply of power. On the spot market, electricity is normally traded by the hour on the day-ahead market. However, the fluctuations in demand and price are a lot faster, and are accelerating. Hence, the trend is increasingly towards shorter settlement periods closer to the actual delivery. These deliveries can be seen as generation pulses. Such balancing services are priced considerably higher than pure electricity production and they offer an additional, valuable revenue stream.

The essence of pulse load is that generation can be started and stopped so rapidly that power can be thought of as supplied in pulses. During such a pulse, the nominal efficiency of the power plant is no longer the most essential parameter. Instead, it is increasingly important to be able to start as quickly as possible, at the lowest possible cost, both in terms of maintenance impact of sudden starts and fuel needed for the start-up process. The pulse efficiency is the net efficiency for the duration of the operating period, including start-up, shut-down and part-load operation.

This paper will study the actual efficiencies and operational costs of different generation technologies during typical pulse intervals. Preliminary results indicate significant potential for savings by optimal matching of generation technology to the length of the pulses.

2. Introduction

Over the past few years, the share of wind and solar power in many grids has increased rapidly, especially in Europe and the USA. Nowadays, a sizeable proportion of all installed capacity is made of intermittent renewable energy sources, a fact that introduces a degree of uncertainty in the power systems previously unheard of. This makes it increasingly difficult to ensure the ever-needed balance between supply and demand in the power systems of the 21st century. It is clear that in order to secure system stability, flexibility will be needed more than ever. Since intermittent renewable power sources are incapable of providing said flexibility in the form of on-demand power, future thermal generation will need to bear the burden and be as flexible as possible.

Once that the need for flexibility is acknowledged, the next step is to research the optimal way of providing it. One characteristic of a flexible plant is the ability to ramp up and down quickly fitting a demanded production time bracket, which we refer to as a *pulse*. We will evaluate different state-of-the-art gas-fired technologies under a set of *test pulses* based on real-life conditions, typical of grids supplying highly electrified societies in Europe. For example, a clear spike in power consumption is noticeable early in the morning of any given weekday, when people tend to wake up, use their home appliances to cook breakfast and get ready to leave their home. A very similar spike takes place in the evening when the population returns home. Another source of pulses, in this case much harder to predict, is the sudden drop in output of the intermittent renewable fleet.

The size and frequency of these pulses raise the need for flexible generation, since the lack of it would jeopardise the stability of the whole power system.

Dealing with pulses

These pulses require the power generation fleet to adapt to them by raising output for a set period of time and returning to the previous level after the pulse is over. The backbone of most modern power systems is made of so-called baseload technologies, those that cannot easily adapt their output in a short time span, or that suffer high efficiency losses if they do so. For example, nuclear power plants and coal power plants, as part of the baseload fleet, are ill-suited to provide on-demand flexible generation, so they will not be taken into consideration for this study.

Gas-fired power is generally used to supply the needed power for these pulses, due to its superior ramping capabilities compared to baseload technology. However, the most widespread solution of that kind are combined cycle gas turbines (CCGT hereafter), which although able to ramp up and down in relatively short periods of time, are still better suited for dealing with stable loads due to their heavy derating under variable load conditions. Since CCGTs are currently the state-of-the-art technology used to deal with load pulses, they will constitute the benchmark for the solution we propose in this paper.

With the aim of reducing the overall cost and improving total system efficiency, we propose the use of a novel technology: combined cycle internal combustion engines. This type of solution consists of a set of gas-fired, medium-speed four-stroke internal combustion engines, each coupled to a generator; paired with a hang-on heat recovery system that uses the exhaust waste heat to feed a Rankine cycle, where a steam turbine is placed. This steam turbine produces extra power compared to a simple cycle solution, and raises the overall electrical efficiency of the system in a substantial manner.

Next, a number of different cases of pulse load operation will be reviewed. The considered time frames for the pulses are four hours, eight hours and 14 hours, whereas the plant sizes taken into consideration will be 100 MW and 400 MW, representing two of the most usual classes in current power systems.

3. Case study: 100 MW power plants

Introduction

The reasoning behind the choice of these concrete examples is their real-life relevance. As it can be seen in Figure 1, the 4-, 8- and 16-hour pulses can be found as recurring patterns in daily demand curves of highly industrialised power systems. Although this concrete figure corresponds to the Japanese daily demand, similar patterns are commonplace in all European power systems

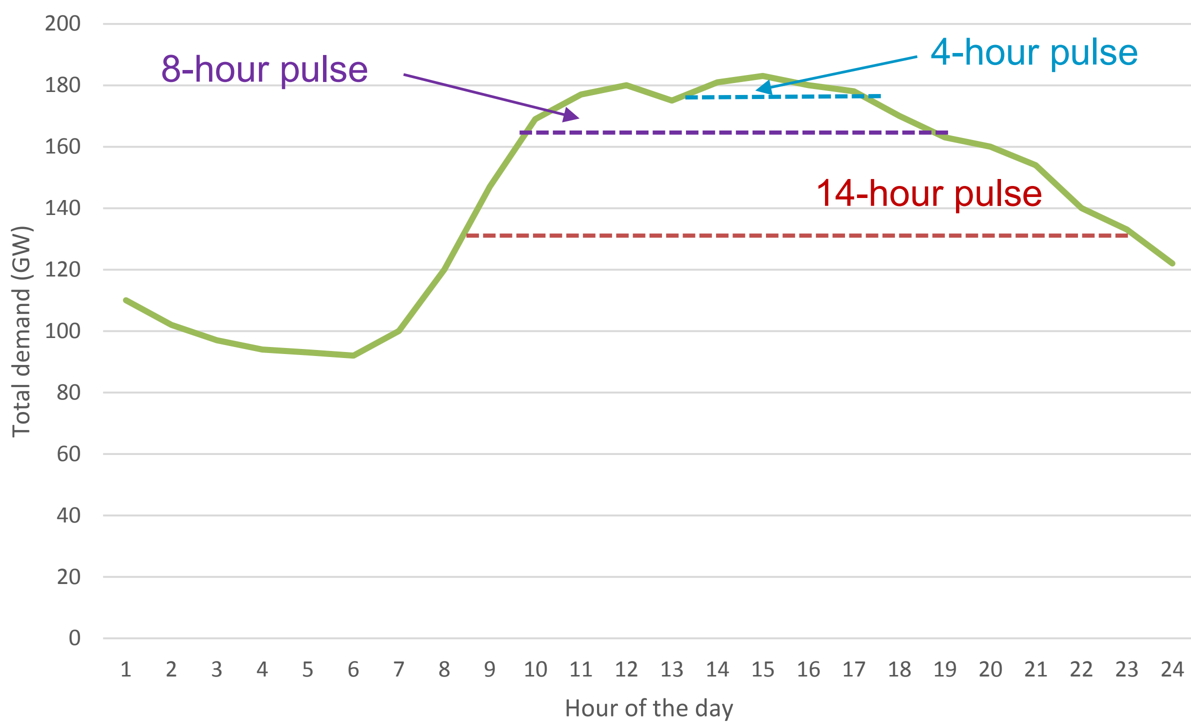

Figure 1: Examples of different pulse loads in a typical daily demand curve

Assumptions

The operational costs considered include the total fuel costs, as well as the total variable operations and maintenance costs (VOM). Both are calculated for the duration of the start-up process, the actually required period of generation, as well as the shut-down time. Additionally, the cost impact on maintenance from the start-up, i.e. the equivalent operating hours (EOH), is also taken into consideration.

The considered technologies are all gas-fired combined cycle power plants, equipped with air-cooled condensers. The comparison is made between state-of-the-art technology based on internal combustion engines (CC ICE) and gas turbines (CCGT). The former technology is based on Wärtsilä's Flexicycle solution, whereas the latter is based on Frame 6 solution (100 MW case) and on a Frame 7 solution (400 MW case). The performance data has been obtained from the latest available versions of engineering calculation software, namely GT Pro for the combined cycle gas turbines and PerfPro for the internal combustion engines.

The fuel price taken into consideration is the import price of natural gas in the European Union as of February 2015, totalling 8.27 USD/MMBTU (28.3 USD/MWh).

Table 1: Performance comparison of 100 MW power plants.

Magnitude	Units	CC ICE	Frame 6 CCGT
Full-load efficiency	%	49,2	51,4
Start-up time	minutes	5 (SC) / 50 (CC)	60
Shut-down time	minutes	1 (SC) / 20 (CC)	30
O&M costs	EUR/MWh	5	3
Start-up costs	EUR/MW	0	64,5

4-hour pulse

A typical CCGT power plant has a start-up time of approximately 60 minutes. Hence, the CCGT plant needs to receive the start command one hour before the actual pulse takes place, a situation that in many cases may prove difficult. Moreover, the energy produced during this start-up hours is typically not reimbursed. The same applies for the shut-down time, which is typically 30 minutes.

On the other hand, a typical ICE in single cycle (SC) mode can be started in only 5 minutes. As soon as the combined cycle equipment is ready, typically in approximately 50 min, the loop can be closed, all while the plant is operating continuously. When it comes to shut-down, the combined cycle ICE plant is able to unload in 20 minutes (1 min when in SC mode).

Hence, the amount of time the ICE plant is run outside the required settlement periods, as defined by the electricity markets, can efficiently be minimised. In other words, the amount of consumed fuel and accumulated running hours can be kept at a minimum.

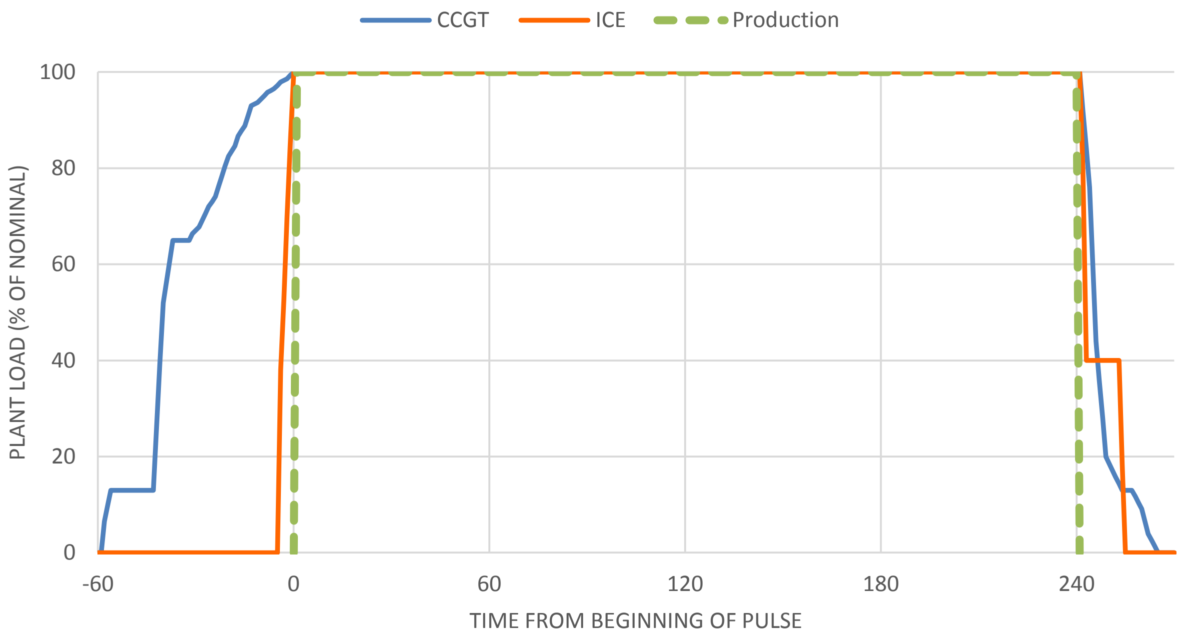

Figure 2: 4-hour pulse, ramp-up and -down required by gas-fired technologies under analysis

Next, the total operating costs of 100 MW power plants during a four hour pulse will be analysed. As seen in Figure 2, first of all the impact of the start-up costs of the CCGT is considerable. Second, when adding the fuel and VOM costs for the one-hour start-up period, the accumulated costs have already reached USD 11,000 at the time when the settlement period begins. Over the four pulse, the higher nominal efficiency of the CCGT is only marginally compensating for these initial costs, compared to the CC ICE. When also considering the costs associated with the shut-down time, the total difference over the full pulse is close to USD 9000, in favour of the CC ICE.

When looking at the four hour pulse in terms of efficiency, the energy produced during the start-up and shut-down periods must not be accounted for, since it is not reimbursable. This energy production is only a by-product of the pulse operation, and not of commercial use. Hence, we will define the overall pulse efficiency as:

$$\eta_p^T = \frac{\int_{t=0}^{t=t_p} P\,(t)\,dt \;-\; \int_{-\infty}^{t=0} P\,(t)\,dt - \int_{t=t_p}^{t=\infty} P\,(t)\,dt}{m_f \cdot LHV_f}$$

Where we have defined $t_p = (4, 8, 16)\ h$, depending on the length of the pulse under analysis in each case. Each of the integrals account for the energy produced in one of three periods of time: before the actual delivery of the energy pulse ($t < 0$), during the pulse ($0 < t < t_p$) and after the pulse is over ($t > tp$). Since the early start-up and the delayed shut-down are needed but do not provide any monetary value being outside of the contracted load pulse, we will discount the energy produced during said periods by subtracting the integrals that quantify out-of-pulse energy delivery. As it can be foreseen, the closer the generation technology is able to match the shape of the demand pulse, the lesser the energy waste. This brings us to an interesting balance between baseload efficiency and operational flexibility, which our overall pulse efficiency (η^T_p) quantifies.

Based on this calculation and the previous assumptions, we find that the overall *pulse efficiency* of the CCGT is 41.0% vs. 46.0% for the CC ICE. We can conclude that in the case of a 4-hour pulse, the far superior operational flexibility of the internal combustion engines outweighs the higher baseload efficiency of the CCGT.

The second part of our analysis will focus on the economic side of the issue. For energy production in current-day competitive markets must be profitable for asset owners, ensuring that the most efficient solution 'on paper' also makes economic sense, is a must.

As we can see in Table 1, the CCGT solution incurs into hefty start-up costs due to the use of start-up fuel and the greatly increased wear and tear of the machinery during the start-up phase, accounted for in the so-called *equivalent operating hours* (EOH) calculation. This factor reduces the time span between maintenance stops and overhauls with each start. This start-up cost puts the CCGT in a disadvantageous situation against the combustion engines, which do not suffer any increased wear and tear nor require extra fuel for starting up. Also, being internal combustion engines capable of starting just five minutes before the beginning of the pulse, the amount of fuel spent in generating non-productive (i.e. out-of-pulse) energy is negligible compared to that of the CCGT solution.

The results of the economic analysis are summed up in Figure 3. We can see that for the case of a 4-hour pulse, the steep start-up cost of the CCGT and its need for one hour of out-of-pulse production cannot be compensated by means of its superior baseload efficiency. Hence, for the typically pulse length of four hours, which covers most morning and evening peaks in western countries, we conclude that the combined cycle internal combustion engine solution is not only technically superior (i.e. it yields a higher overall pulse efficiency), but also economically superior by means of a reduced operation cost compared to that of a CCGT.

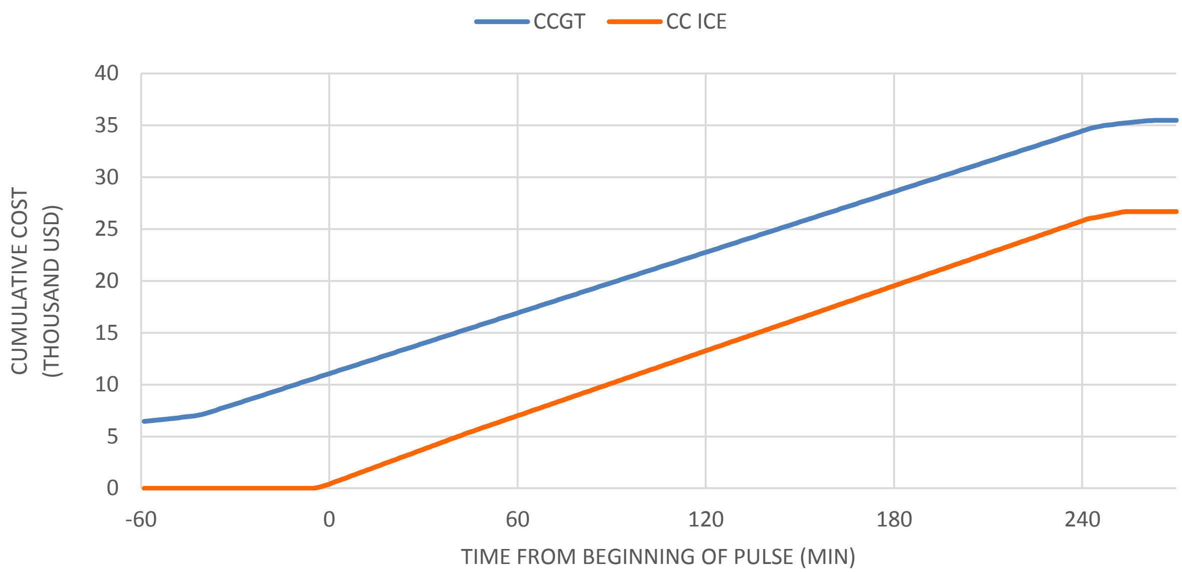

Figure 3: 4-hour pulse production – Fuel, O&M and start-up costs (100 MW power plants)

8-hour and 14-hour pulse

Similarly, eight and 14 hours pulses have been analysed for the 100 MW power plants. A summary of the overall *pulse efficiencies* for these periods is presented in Figure 4. Hence, not even during a 14 hour pulse the higher nominal efficiency of the CCGT is sufficient to compensate for the energy waste as a result of slower start-up and shut-down: the CC ICE solution is still a more efficient option.

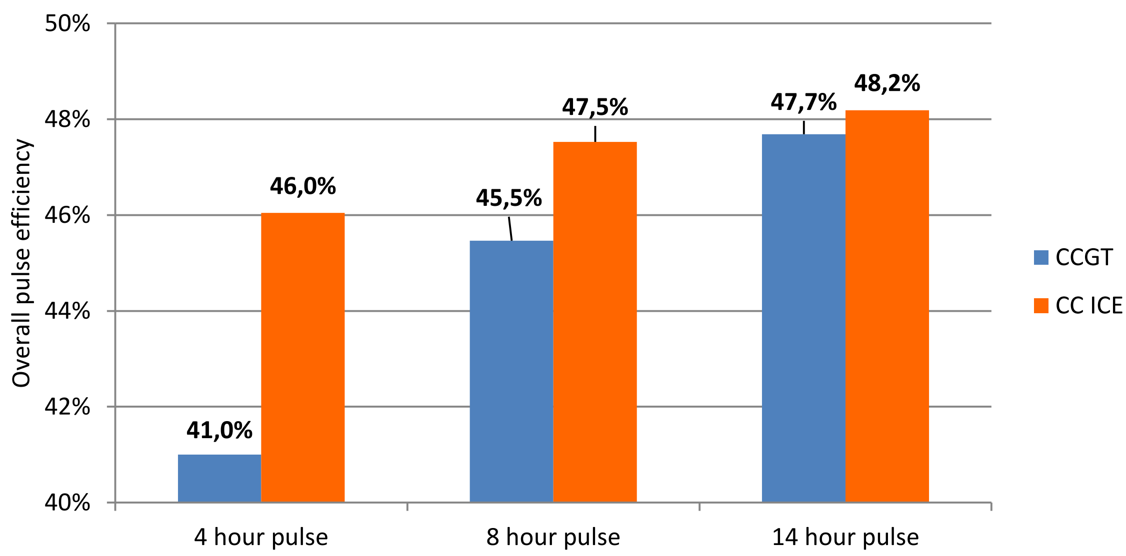

Figure 4: Pulse efficiencies (including Fuel, O&M and start-up costs) for 100 MW power plants

Money-wise, the conclusions are similar: even in the most unfavourable case for the CC ICE, that of the longer 14-hour pulse, the 100 MW CCGT solution still incurs in a higher cost than the internal combustion engines, leaving us with a very clear preference towards the latter when it comes to dealing with the challenging load pulses that are commonplace in 21st century power systems.

4. Case study: 400 MW power plants

In a similar fashion to that used for analysing 100 MW power plant solutions in the previous chapter, we will now present a comparison of the pulse load efficiencies of a Frame 7 based CCGT solution and a scaled-up version of the CC ICE solution based on Wärtsilä's Flexicycle technology. Table 2 provides a comparison of the technical performance of these solutions.

Table 2: Performance comparison of 400 MW power plants.

Magnitude	Units	CC ICE	Frame 7 CCGT
Full-load efficiency	%	49,2	54.0
Start-up time	minutes	5 (SC) / 50 (CC)	60
Shut-down time	minutes	1 (SC) / 20 (CC)	30
O&M costs	EUR/MWh	5	3
Start-up costs	EUR/MW	0	64,5

4-hour, 8-hour and 14-hour pulses

An overview of the calculated pulse efficiencies for the 400 MW CCGT and CC ICE solutions is presented in Figure 5.

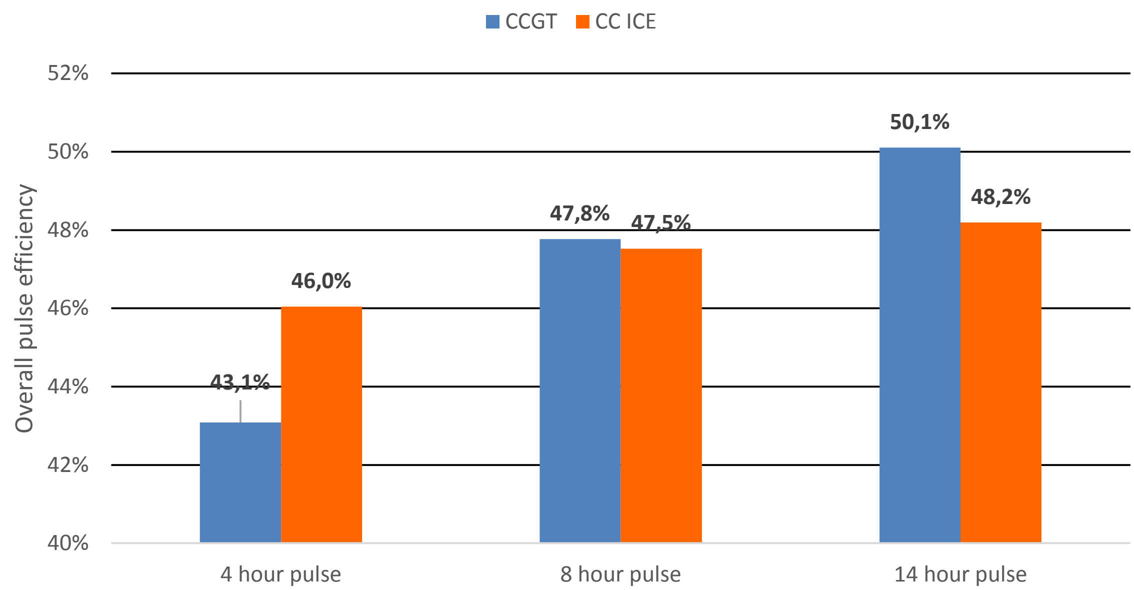

Figure 5: Pulse efficiencies (including Fuel, O&M and start-up costs) for 400 MW power plants.

It is in this case, where larger power plants are evaluated, that the results turn out most interesting: During the 4-hour pulse, the overall efficiency is almost 3 %-units higher for CC ICE solution. However, we can observe a technical break-even of the efficiencies occurring briefly before 8 hours.

For lengthier pulses, the CCGT becomes the more efficient option, surpassing the CC ICE by a slim margin. However, it is important to notice that even though the pulse efficiency of the CCGT is slightly higher than that of the CC ICE, **the *total operational costs* are still higher**.

In the 8-hour case, although the overall pulse efficiency of the 400 MW CCGT is 0.3 percent units higher than that of the CC ICE, **the overall cost generated by the CCGT is still 12 percent higher**, which is a very remarkable difference. Even in the 14-hour case, were the CCGT, best suited for baseload operation, wins clearly in terms of overall pulse efficiency, **the CC ICE retains a 0.3 percent cost advantage**.

The main reason for this is the EOH factor, which although does not affect the pulse efficiency as such, introduces a very real cost that must be accounted for, in the form of increased maintenance and overhaul needs. The total costs for the 8- and 14-hour pulses in the 400 MW case are presented in Figure 6 and Figure 7.

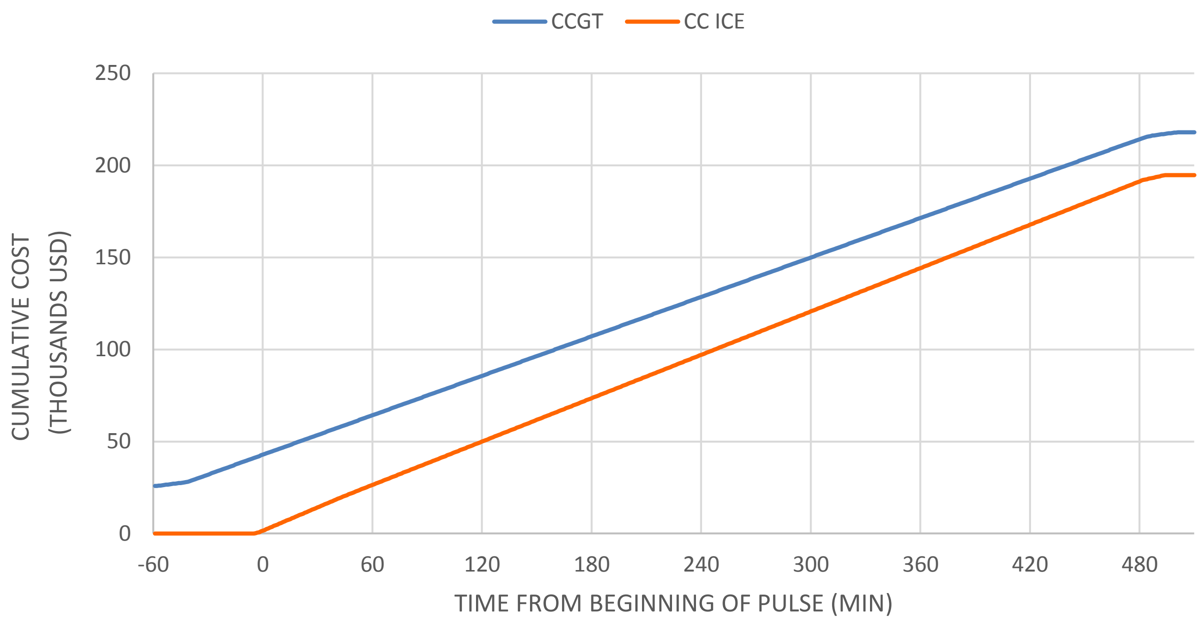

Figure 6: 8-hour pulse production – Fuel, O&M and start-up costs (400 MW power plants)

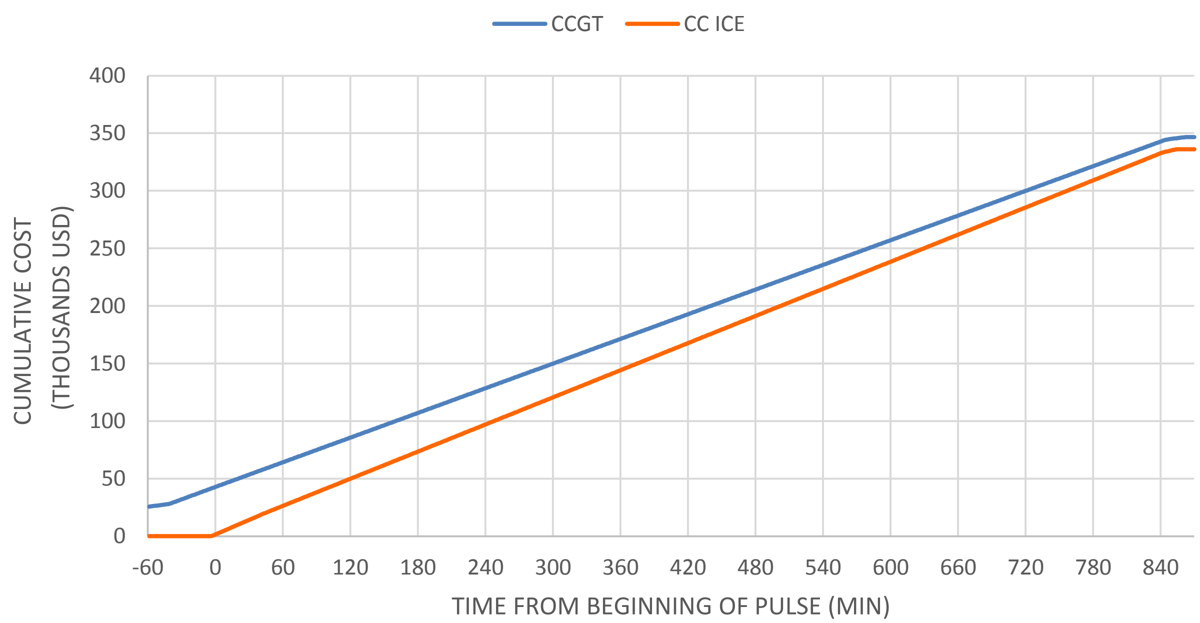

Figure 7: 14-hour pulse production – Fuel, O&M and start-up costs (400 MW power plants)

5. Conclusions

As a result of our technical and economic analysis, we can conclude that the shorter a single pulse of power generation is, the greater the importance of reaching full load quickly. This emphasis on flexibility easily outweighs a higher baseload efficiency, and for that matter the evaluation criteria in power plant projects must be rethought. In summary, we conclude that

- For short & medium pulses, 4 and 8 hours, an internal combustion engine-fired combined cycle (such as Wärtsilä´s Flexicycle solution) is a more competitive option than both small-scale (100 MW) and large-scale (400 MW) CCGTs.

- Even though the 400 MW CCGT has a higher average efficiency than Flexicycle during an 8 hour pulse, its total operational costs are higher (due to the start-up costs and increased maintenance needs).

- For long pulses, 14 hours, Flexicycle is a more competitive option than small-scale (100 MW) CCGTs.

- Even though the 400 MW CCGT has considerably higher average efficiency than Flexicycle during a 14 hour pulse, their total operational costs are still higher than that of the internal combustion engine-based solution.

The following chart serves as a summary of the undergone modelling and presents the best solution in both the technical (overall pulse efficiency) and financial (overall cost) terms, for each of the scenarios under analysis.

	100 MW plant		400 MW plant	
Length of pulse	Better overall pulse efficiency	Better overall cost	Better overall pulse efficiency	Better overall cost
4 hours	**CC ICE**	**CC ICE**	**CC ICE**	**CC ICE**
8 hours	**CC ICE**	**CC ICE**	**CCGT**	**CC ICE**
14 hours	**CC ICE**	**CC ICE**	**CCGT**	**CC ICE**