Hybrid Energy Solutions for Decarbonization of Islands & Remote Areas

(Introduction, Design Considerations and Real-world Example)

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***Abstract* — Renewable energy is intermittent by nature, so they are often backed up by fossil thermal power (in many cases fuel oil with a high carbon footprint). Hybridizing such power systems by integrating biofuels- and hydrogen-capable power generation, energy storage, flywheels, and synchronous condensers for grid balancing paves the way to a more decarbonized, sustainable, and even less costly energy system. Remote, off-grid areas have a growing need for sustainable energy that is reliable and affordable. Hybrid systems are being developed with the goal of reducing – or even preventing – carbon emissions via increasing the share of renewable energy. Smartly coordinated microgrids, hybrid power plants and energy parks can make a tremendous contribution to decarbonization. Storage systems enable higher utilization of renewable energy (less curtailment) and reduce the need for additional backup power. This also leads to reduced fuel consumption and dependency on fuel imports. Equipped with autonomously operating control systems utilizing real-time algorithms and weather forecast, hybrid systems can produce first-class results in an economical and environmentally optimized manner.**

Siemens Energy offers several pathways for transforming remote energy generation from fossil to less carbon-intensive and renewables-dominated power generation systems. The decarbonization depths depends on the specific customer goals, RE potential and availability of financing. Starting with measures to increase efficiency of existing technology, over “fuel shift and hybridization” up to “deep decarbonization” technologies, SE has proven to be a reliable, efficient, and innovative partner developing solutions over lifetime without the risk of stranded assets, and one of the very few OEMs with most of the green solution technologies in-house.

On the example of a real-world application, it shall be shown how Siemens Energy supports the energy transition of customers towards a cleaner and more sustainable energy future. Special focus is put on the impact of different levels of decarbonization and the respective effects on CO_2 reduction and economics.

Keywords: Decarbonization, Hybrid Power Plant, LCoE, Energy System Design

I. INTRODUCTION

Today, several power system models are available to solve the energy trilemma of decarbonization, security of supply and economics. Being isolated from large power grids, like the case for islands or other remote locations (e.g., mining sites), adds additional complexity in terms of grid stability. How these challenges can be overcome, depending on the degree of decarbonization envisaged, as well as the impact on economics (Opex and Capex), shall be discussed in this paper.

Especially for islands, the threat of rising sea levels caused by global warming is tremendous. Therefore, it is the own interest of island countries to lead by example and substantially reduce their emissions of greenhouse gases. Such examples can motivate others to follow this path. During the COP26 conference [1], the role of pollutants with high GWP (global warming potential) besides CO_2 was discussed. A main contributor to global warming is methane (CH_4) with a CO_2-equivalent factor of 28 (GWP100) or 81 (GWP20). Therefore, in a so-called *Methane Moment* [2], much focus was brought to ideas on how to speed up efforts to reduce methane emissions in power generation. Technological evolution, but especially the choice of gas-based power generation technology with lowest or no methane slippage (example: gas turbines) can provide already today a viable option to significantly reduce methane emissions in the power sector.

So, real decarbonization needs substantial CO_2 and CO_2-equivalent emission reductions in all sectors, but focus is currently on the power sector as other sectors are much harder to decarbonize (e.g., steel and cement industries). On the other hand, budgets are limited, as well as third party financing support or subsidies. Viable economic solutions accounting for reduction of emissions and power system stability and reliability are complex and will finally require a combination of many different power technologies like generation, storage, and grid supportive systems. A major hurdle currently in the task to increase power harvesting of renewables beyond the real-time demand is the lack of large storage technologies at low cost. Once power storage is available in the size of tens or more GWhs short and long-term, a large-scale transition from fossil to renewable power will be feasible. But for the foreseeable future, natural gas-based power generation offers a flexible solution for the current challenges and the potential of switching to CO_2-neutral fuels like hydrogen and other e-fuels once those are available in large quantities.

Since fuel cost on islands tend to be higher than on mainland (less potential for economies of scale), a high fuel efficiency (of gas-based generation) is of utmost importance. This already leads to achieving two of the three goals: reduction of CO_2 and cost of fuel. To secure supply, sufficient reserve capacity must always be available to satisfy power demand when renewable energy production is insufficient. Siemens Energy gas turbines for example are well suited to provide base and reserve power and, in combination with storage technology, enable 24/7 power supply at low carbon footprint for island grids.

Our focus is beyond pure equipment provider. We aim to support our customers on their journey towards a decarbonized but still profitable business. Therefore, we offer an optimization service to evaluate the customers entire power generation fleet and integrate all different existing assets into the planning of his future power system. This allows for best utilization of the existing fleet together with new equipment and minimization of invest and opex cost.

II. DESIGNING A HYBRID POWER SYSTEM

A. Islands and Remote locations: Major Challenges for Hybrid Power Generation

Before diving into the technologies necessary to win the decarbonization challenge, let us first summarize the most relevant areas of concern for the power systems of small island and remote locations:

Security of supply: The load or demand curve of the end customers must be met at any time 24/7/365. For very remote areas, a reliable fuel supply chain is to be considered as well.

Economics: Power systems must be designed to provide electric or thermal power at lowest possible cost. Optimization and use of existing power generation assets as well as incorporating low-cost renewable energy are key. Multi-use of equipment for generation and grid balancing will further reduce cost

Environment: Pollution should always be limited to the lowest possible amount. This includes local emissions (NO_x, SO_x, CO, PM, etc.) as well as global climate harmful GHG substances (CO_2, CH_4, SF_6, N_2O, etc.

Individual application or customer specific requirements of all kinds

Balancing out all these single tasks to the optimum turns out to be a very complex evaluation. There is no one-size-fits-all, and the many task and technology-related dimensions must be considered and optimized simultaneously. It is of utmost importance to use numerical optimization tools for this analysis and, at the same time, have dedicated experts at hand to conduct a reality check of the results.

B. Hybrid Technologies

To solve the optimization problem of a hybrid power system, the elements the optimizer can use have to be defined. For each of these elements, many features and specifics must be provided like size, cost, efficiency, maintenance details and so on. Exemplary, we will just name the most common technologies here.

Renewable Power Generation:

- Solar power, either PV or CSP
- Wind power, on- and offshore
- Hydro power
- Geothermal

Thermal Power Generation

- Gas Turbine (GT)
- Gas Engine (RICE)
- Steam Turbine (ST)

Storage Technologies

- Electrical Storage
    - Li-Ion BESS
    - Redox Flow BESS
    - Super Capacitors
- Mechanical Storage
    - Flywheel
    - Pumped Hydro
    - Compressed or Liquid Air
- Chemical Storage
    - Hydrogen with Fuel Cell (or thermal re-electrification with GTs or RICE)
    - E-fuels / Power-to-X (NH3, CH3OH, etc.)
- Thermal Storage
    - ETES (hot stones)
    - Molten Salt

C. Solution for the Energy System

In order to obtain a cost-optimized solution which complies with all requirements, a large amount of information is necessary upfront to be entered into the optimization software. Examples of required data:

- Demand / load profile (extremely important, data accuracy highly effects the results)
- Optimization objectives like LCoE, emission reduction, cash flow and profits, supply security, etc.
- Degree of decarbonization aimed for
- Existing fleet / assets, cost of operation and potential lifetime extensions
- Potential for renewable energy (climate data: wind and solar profiles)

- Preferred technologies for pre-selection
- Cost models for components
- Etc.…

Time series profiles are expected to be hourly for a full year. Once all data is implemented, the energy system design tool performs a technology selection and sizing based on the customer optimization objectives. The selection complies to all boundary conditions applied at every hour throughout a year. Basically, the results will show a design proposal incl. generation and storage asset sizes as well as associated Capex and Opex. The total cost of energy (Euro or any other currency) will be calculated as well as other economic and ecological results. Additionally, an optimal operation schedule will be offered by the software.

In order to consider very short-term effects like, for example, sub-second grid-related events (e.g., unexpected shutdowns of power generators or transformers), but also abrupt changes on the demand side, it is recommended to add a grid stability study. Potential grid faults can be simulated, and the robustness of the grid can be verified especially in times with large RE production and low online system inertia.

D. *Grid Stability*

In the classic, centralized mainland grid structures, large conventional power plants provide grid support services as frequency balancing (high inertia) and compensate the reactive power necessary for transmission and distribution grids and the local grid dominated by end-consumers demand (includes the task of voltage balancing as well). In addition, short circuit power is provided for fault detection. For small, isolated grids, all these tasks need to be accomplished by the microgrid itself. In addition, increased integration of intermittent renewable energy can cause fluctuations in the power grid as the contribution to inertia is zero in the case of solar power and low in the case of wind power.

Potential fixes to these issues are the integration of flexible, dispatchable power generators like gas turbines or gas engines. These technologies can ramp up from stand still to full load within minutes and compensate for lower renewable power dispatch as these are normally forecastable on the timescale of minutes up to hours. On the other hand, grid events are sub-second and require instant reaction. Basically, there are two ways of handling this. Either rotating masses, synchronously connected to the grid, can add physical inertia, or batteries can provide so-called synthetic inertia if they are equipped to do so. Flywheels and synchronous condensers offer grid stability but come at additional cost. Turbines provide high inertia, frequency stabilization and high short-circuit voltage. Engines also exhibit such features but on a smaller scale and may still require additional rotating mass like flywheels. Smartly designed, **a gas turbine can also serve as synchronous condenser and flywheel** when the electric generator is decoupled from the turbine. The minor investment into a SSS clutch between turbine and electric generator can save large, stand-alone investments into synchronous condenser or flywheels (not even mentioning the savings in space plus additional grid connections).

E. *Renewables Integration: Capex and Opex Effects*

The graph in *Figure 1* shows the effects of the transition to decarbonization on Capex (red) and Opex (blue). The left side ("100% diesel/NG/…") describes an existing, fully depreciated asset consisting mainly of fossil fuel generation with almost pure Opex expenditures. The Capex figure mainly reflects investments into lifetime extensions of the existing gensets. Adding renewables to the power system requires increasing Capex, which is overcompensated by lower Opex. Up to a certain threshold value it is clearly visible that investments in renewable energy substantially lower the LCOE of power systems. In addition, a smaller environmental footprint is achieved, so undoubtedly a win-win situation emerges here.

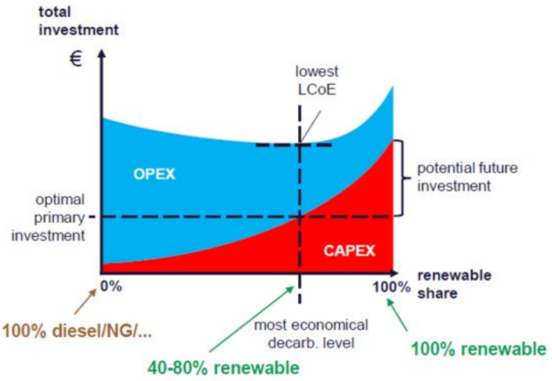

Figure 1: Capex and Opex based on decarbonization level: From existing fossil power generation (left), adding renewables up to 100% renewable power systems (right). Please note that the specific shape of the curves varies a lot depending on the project boundaries.

A further increase of the RE share for *deep decarbonization* requires additional investments disproportionately above the current economic optimum to better harvest and time-shift the renewable energy and produce green fuels for long-term storage. Unfortunately, this behavior comes from the intermittency of renewable power sources (except hydro power), and provisions must be made in the rare event of dark doldrums (long time periods without sun and wind). As a transitory solution, dispatchable power can be applied to back up the power system in such times with low or no renewable energy.

F. *Fuel Flexibility*

A fuel flexible power generation asset can be of major value for a plant operator. Independence of fuel suppliers on the one hand, but also readiness for future low-carbon fuels improves investment security and helps avoid stranding of assets. **Gas-based power generation does not mandate the use of natural gas as many think**. Such generators allow the use of other gases such as **hydrogen**, **ammonia**, LPG, biogas, and of course synthetical natural gas produced by CO_2-neutral processes. Although not available in large quantities today, governments around the world recognize the advantages of CO_2 -neutral (and free) fuels and provide funding for the development of e.g., hydrogen production facilities fueled mainly by renewable energy. Such fuels will be expensive at first, but unavoidable to fulfill the tough CO_2 and other GHG targets agreed in the past and tightened during the COP26 conference [1].

Mainly two different technologies can efficiently and economically convert gases of different kind to electricity today: gas turbines and gas engines. Each comes with their own set of advantages and disadvantages, not to be covered in detail in this article. Nevertheless, Siemens Energy as OEM of both product categories, extensively analyzed them to figure out which one is best suited for the different applications and customer demands. Briefly, gas turbines exhibit a high value for grid stabilization like inertia and therewith high immediate response capabilities in the case of grid issues. Also, no methane slip is observed in turbines while in RICE engines we still see high methane emissions contributing to global warming (unfortunately also during use of biomethane which typically is classified as a green fuel). On the other hand, RICE engines have high simple cycle efficiency and compared to an open cycle turbine, emit less CO_2. But not CO_2 -equivalent: as methane slip adds to the CO_2 -eq. footprint, it sometimes offsets the emission advantages of SC efficiency. Turbines, on the other hand, can close the heat cycle by adding a steam turbine and a heat recovery boiler, and thereby increasing the total net efficiency of the plant up to 50%. CCPP have net efficiencies over 50% and, depending on the GT type and the ambient conditions, over 60%, significantly surpassing engine efficiencies. Start-up times for engines are typically lower than turbines, but aero derivative GTs come very close to start times of engines. Lastly, looking at the fuel flexibility of both technologies, the picture is mixed. Generally speaking, engines have advantages when it comes to liquid fuel flexibility while turbines tend to have better flexibility for gaseous fuels. All gas generation OEMs are heavily researching to improve the hydrogen combustion capabilities of their technologies. But in the power generation area comprising unit sizes >5MW, there is today an advantage for turbines. The combustion challenges of high H2/NG blends seem to be bigger for engines than for turbines. This is just a snapshot of today's situation, and the authors cannot predict if this picture may change in the future. Clearly observable is that already 50 MW turbines capable of running on 75% H2/NG blends (in dry mode without water inlet spraying) are purchasable in the markets, whereas engines running on such high H2/NG blends are typically of ~1 MW in size.

For more details on the comparison of features of engines and turbines it is referred to the Siemens Energy internet page easily accessible on the web [4].

G. *Optimization of business case in operation*

Once the power system is optimally designed, a second optimization step is needed to ensure best asset utilization during operation. This is achieved by an *Energy Management System* fully integrated into the controls system of the microgrid. Within a forecast module, the inputs for load, weather and possibly prices (fuel, electricity, but also potential penalties) are assembled online. A complex solver algorithm combines that with available data such as capacity restrictions (i.e., due to maintenance) and measurements (such as temperatures, storage levels, etc.) to derive an optimized generation schedule which meets all customer targets like high reliability, low Opex or low emissions.

This schedule is forwarded to the microgrid control in defined intervals of 15 minutes. The microgrid control in turn will operate the assets in **real-time** according to the schedule as long as the electrical stability is guaranteed. In case of forecast deviations like solar irradiation lower than predicted, the microgrid control system will overrule the schedule and initiate proper measures to ensure grid stability at any time.

III. EXAMPLE: ISLAND CASE

In this section decarbonization pathways for a remote island in a tropical maritime environment with a size of >100 km² and more than 100 thousand inhabitants shall be presented. The results are very similar to what was discussed with a customer during a real project opportunity. A high degree of decarbonization and independency of fuel imports were the major objectives of the customer besides lowering the overall cost of energy. As a service, different levels of transition to decarbonization have been analyzed to clarify the effects of larger investments into hybrid solution and their benefits to the environment as well as to the overall cost of energy.

The results provided below are always related to the first *initial situation* case.

A. *Initial Situation*

The total demand for electric power summed up to about 1,000 GWh per year, mainly for private homes and industry. 120 MW older RICE engines cover the vast portion of this demand (at very low net efficiency compared to today's state-of-the-art technology). Significant pollution was caused additionally as these engines were fueled by HFO which was imported to the island at high cost. This made the power system dependent to external fuel supply and vulnerable to price fluctuations. All these factors lead to high LCoE (levelized cost of electricity) meaning a large burden on the economics because to further develop the industry, an increase in power supply was unavoidable.

It shall be mentioned that some minor installations of PV and wind were also in the system, but due to their negligible size they have been excluded from this analysis.

On short:

- 120 MW highly pollutant HFO-driven power supply (liquid fuel RICE)
- No renewables, but good potential for wind power
- LCOE of ~13.7 €ct./kWh
- 1 M€ capex required for lifetime extension of the existing RICE HFO fleet

In the renewables power scenarios shown below, still the existing fossil fleet of 120 MW RICE engines would be available and run on HFO as the complete infrastructure and supply chain for HFO delivery should stay unchanged. Potential measures to switch these engines to cleaner fuels are available but would require a new design of the fuel supply chain and all surrounding systems such a fuel transition come with would mean significant additional invest cost and were therefore not part of this study.

B. 'Entry-level' Installation of Renewable Power

In a first step into decarbonization, an investment totaling 71 M€ into renewable energy was modeled. A RE penetration of 28% resulted from this invest (this number relates to the GWh generated, not the installed capacity). The following changes to the power system were achieved:

- 40 MW wind power
- 13 MW solar PV
- 20 MWh BESS (Li-Ion)
- Reduction of CO2: 28% (!)
- Reduction in Opex: 16%
- Reduction in LCOE down to ~12.2 €ct./kWh (~11%)

Although in this scenario still the largest portion of energy is produced by HFO-RICEs, the cost of energy is already substantially reduced (mainly due to high-cost fuel savings). Likewise, the emission of CO_2 is lowered by 28%, not even mentioning all the other pollutants caused by combustion of HFO which will not be covered here; there is abundance material in the literature available. The LCoE reduces by an astounding 11% (with investment cost already considered). Supposed the budget for such an investment is available, this step would be already a 'no-brainer' from economic (and of course ecological) standpoint.

C. 'Substantial 1' Installation of Renewable Power

For power providers aiming for a much larger decarbonization effort, and capable to make larger invests, the next step would be a much bolder one. Here, an investment of 185 M€ into the power system was modeled. The renewable penetration would increase to 70% while Opex would reduce by 43%. The changes to the power system in short:

- 140 MW wind power
- 26 MW solar PV
- 20 MWh BESS (Li-Ion)
- Reduction of CO2: 70%
- Reduction in Opex: 43%
- Reduction in LCOE down to ~9.8 €ct./kWh (~28%)

Compared to the entry level state, the amount of wind power has been more than tripled. The reason for that is the abundance of wind potential with high speeds which make the choice for this power source much more attractive than solar PV. Nevertheless, also solar power contributes to the island power mix in this scenario. Here, the size of BESS storage was kept equal to the entry case to show the difference with (next case) and without it.

The amount of reduced CO_2 emission is a staggering 70% and, having in mind the substantial decrease in LCoE as well, can make people wonder why such investments are not being made way more often. Of course, financing is a big hurdle in many cases, and private equity does not come at low cost. But hopefully, in future, sustainability investment funds with high focus on CO_2 reduction and ecologic friendly investments may provide liquidity for such projects.

D. 'Substantial 2' Installation of Renewable Power

Enabling higher penetration of renewables not only depends on the total installed wind and solar capacity. In times of surplus power production and full batteries, curtailment of renewable power is unavoidable to not destabilize the power grid. Avoiding such curtailment by e.g., larger batteries does have a substantial impact on the utilization of renewable energy. Our *Substantial 2* scenario exactly images that. With 'just' 6 M€ additional investment compared to *Substantial 1* scenario, the total battery capacity doubles to 40 MWh, and the other KPIs improve considerably:

- 140 MW wind power
- 26 MW solar PV
- 40 MWh BESS (Li-Ion)
- Reduction of CO2: 75%
- Reduction in Opex: 49%
- Reduction in LCOE down to ~9.0 €ct./kWh (~34%)

The impact of the fairly small investment into additional storage capacity shows large effects on CO_2 reduction, Opex and LCOE. The difference in LCOE achieved by this last measure is 0.8 €ct./kWh and sums up to 8 M€ per year (payback period of less than a year). It also shows the importance of the system design optimization process as a holistic approach. Only a numerical investigation with advanced software can ensure that each € of additional (marginal) investment is placed into the most value adding technology.

Finally, the results of the last scenario compared to the initial case shall be outlined here. Still considering the same power demand of 1000 GWh/y and a LCOE difference of 4.7 €ct./kWh, the **total power system cost would lower by an astounding 47 M€ per year** (during the asset's lifetime, includes already financing annuities). Another huge winner of this scenario is the environment: the amount of **CO_2 saved would equal 450.000 tons yearly** (assuming 600g/kWh_el, still HFO as a fuel). Same %-wise reductions would apply to all other pollutants caused by the combustion of HFO and lead to a tremendous improvement of life quality for residents living nearby such plants. Equally, the **dependency of fuel imports** would strongly decrease as the amount of fuel consumed would tumble down to **25%** of current values.

E. Potential '100% Decarbonization' Installation of Renewable Power

This case has not been analyzed in this study; nevertheless, some general considerations shall be provided here which resulted from similar case studies. Customers envisaging a maximum decarbonized energy system will have to engage with long-term power storage. Hydrogen [3] is currently developing into such a role as it serves multiple use cases:

- Ease of production (electrolysis)
- Reduction of renewable energy curtailment
- **Dispatchable** re-electrification in GTs, RICE, or fuel cells
- Feedstock for "Power-to-X" [3] e-fuels like ammonia NH_3, methanol CH_3OH, or e-NG
- Feedstock for other industries
- Fuel in the mobility sector
- Enabler for decarbonization of other sectors, e.g., steel industry

Hydrogen has a huge potential for decarbonization. The only constraint currently is its high production cost and the low energy density per volume because the storage of pure hydrogen either requires large volumes, high compression, or liquefaction resulting in high cost and significant decrease of roundtrip efficiencies.

But once produced and stored, it can serve as a backup fuel in times of low RE production. Used in gas turbines for example would enable all the benefits of having a dispatchable genset and grid stability capabilities that turbines have, and at the same time be CO_2 free (running on 100% H2). The entire production chain could also be used as flexible demand load because they can be quickly shut off in times of power fluctuations or shortfalls. Having such a balancing degree of freedom in the power system can take pressure of the power supply side and not only ensure fast reaction time but also lower stress on the power generation equipment with positive effects on the service lifetime.

F. Additional grid stability investments

It should be mentioned as well that additional investments into grid reliability might become necessary to balance out the grid at any time. The topic was briefly touched, but not in too much detail. In RE dominated power systems, the low share of rotating equipment can cause disabilities to normalize grid fluctuations or more severe grid events. To a certain extent batteries can provide balancing power if they are designed to do so, but there are limitations to be considered. Large rotating masses, synchronously connected to the grid, provide immediate response to sub-second grid events and can prevent brownouts or blackouts. Such large rotating masses also increase the response time in case of grid events by lowering the RoCoF (rate of change of frequency, this number describes how fast the frequency of a power system changes in the case of a grid event). Additionally, high short circuit power (voltage and amps) as well as re-active power compensation can natively be provided by rotating gas-based generation. Such features require extensive electrics and electronics if they shall be provided by BESS systems.

In future, for largely decarbonized remote power grids with low or almost no rotating inertia, a strong focus on grid stability is mandatory to avoid power imbalances causing blackouts.

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ABBREVIATIONS USED

SE	Siemens Energy AG
GT	Gas turbine
RICE	Reciprocating internal combustion engine
BESS	Battery Energy Storage System
Genset	Power generation unit, e.g., a turbine or an engine
RE / RES	Renewable Energy / RE System
PV	Photovoltaics
CSP	Concentrated Solar Power
COP21/26	UN Framework Convention on Climate Change Conference (2021 in Glasgow)
GHG	Greenhouse Gas
GWP	Global Warming Potential
OEM	Original Equipment Manufacturer
SSS	Synchro-self-shifting. Coupling type with automatic engagement mechanism
LPG	Liquid Petroleum Gas
HFO	Heavy Fuel Oil
NG	Natural gas (mostly methane)
e-NG	synthetic NG (produced with RE, CO_2 neutral)
H2	Hydrogen
NH_3	Ammonia
CH_4	Methane
CH_3OH	Methanol
LCoE	Levelized cost of electricity
Capex	Capital expenditures (invest cost)
Opex	Operational expenditures