Operating Hybrid Energy Systems at Lowest Cost by Implementation of Real-Time Local Market

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***Abstract*— The transformation of energy systems from thermal to renewable - and typically volatile - generation has become feasible in any part of the world by drastic reduction of the cost of solar and wind generation assets. However, RE dominated energy systems require substantial changes in system design and management, specifically to ensure adequate energy storage and system coordination. The need and cost of energy storage can substantially be reduced by integrating demand flexibility, and in system co-ordination the roles of generation and consumption must be swapped: While previously generation followed given demand, now consumption must follow given generation. A new technology to achieve this - originally conceived for isolated micro grids - has now been successfully adapted and implemented in a grid-connected micro grid in Germany. Multiple energy sources (grid, PV, CHP) and multiple flexible consumers (thermal, electric vehicle charging, household appliances) are coordinated for maximum collective and individual benefit. Even before the installation of the first battery, intelligently coordinated operation of a principally unlimited number of flexibilities leads to increased self-consumption from 50 to 80%, with the associated benefits of financial savings on energy as well as grid relief and even stability contribution. We present the principle and results achieved in the reference project, together with suggestions to adapt it to isolated micro grids.**

Keywords: RE dominated systems, demand side integration, flexibility, energy system co-ordination, micro grid, local energy market

I. INTRODUCTION AND MOTIVATION

Traditional energy management uses readily available flexibility at the generation side to ensure demand is matched at any time. With the advent of volatile renewable energy sources (solar, wind) a certain degree of their integration was achieved by the flexibility of thermal plants (often diesel gensets) that also can balance RE variations. However, this opportunity disappears latest when renewable sources cover 100% of instantaneous load, as thermal plant cannot generate “negative” power. At this point, electric energy storage must be introduced. Even though battery cost is dropping, it still accounts for a substantial share of total systems cost, and for system stability reasons, it must be introduced well before renewables cover 100% of instantaneous load. An alternative to the provision of large and expensive electricity storage capacity in situations with high volatile RE shares is the inclusion of demand side flexibility: As electricity storage is only needed for the mismatch between production and consumption patterns, the better consumption can be adapted to production, the less electricity storage is required.

The focus of this paper therefore is on flexibility. Its value – and therefore the expected return on efforts to harvest flexibility - depends on the difference between LCOE of fossil versus renewable generation. Already 2011 this difference was >25 ct/kWh for Diesel vs. PV on the Maldives, which was the original trigger of the work presented here.

II. REDUCED STORAGE COST BY DEMAND FLEXIBILITY

While energy uses exist that are not flexible (such as lighting), many applications are. So far, they were not operated in a flexible manner just because there was no need to do so. Flexibility assets like water storage towers were de-activated and even destructed as electric pumps could maintain the required pressure in the hydraulic system powered by thermal plants 24/7. Note that from an energy system perspective, shifted demand often cannot be distinguished from a battery: if a load of 1 kW is not operated from 9-10h, but instead from 10-11h, the grid sees a reduced load ("discharging" of a battery relative to the original pattern) in the period 9-10h, and an additional load ("charging" of a battery) in the period 10-11h. As a result, the grid sees a "virtual battery" with a capacity of 1 kWh that has been added to the system by mere shifting of an existing load! This "virtual battery" does not require any investment nor cooling, has no aging or losses, and is not produced with rare or potentially harmful materials.

Assessments of demand side flexibility potential typically are conservative because no mechanisms exist to include typical household loads (which are very small but also very numerous), and the available mechanisms create complicated contractual and operational overheads (negotiations and obligation to commit to schedules). However, substantial potential of load shifting exists not only in large industrial and infrastructure applications (such a water pumping, processing and desalination, energy for production processes), but also at commercial and household level (cooling, heating, washing machines). The ongoing electrification (in the process of de-carbonisation) of sectors that previously were powered by fossils (such as mobility and heating) adds large amounts of flexibility to electricity systems. Some flexibility like time-shifted EV charging comes "for free", i.e., without any additional cost caused by investments in storage or energy losses. Even in thermal applications where thermal losses and investment in thermal storage capacity must be considered, moving the energy storage function from the electric to the thermal system side can slash storage cost by up to a factor of 100 [1]. It is obvious that battery cost would have to continue falling for decades to match them, and investments in demand flexibility such as larger water tanks will provide higher returns for a long time to come! Therefore, full leverage of such decentral flexibility is a major key to cost-efficient energy storage and thus an economically viable energy system transformation.

III. MOTIVATING, ENABLING AND REWARDING DEMAND FLEXIBILITY

Assume you are in charge of a water supply infrastructure or own an asset like a washing machine which possesses valuable flexibility – how could you make it productive for the energy system? Would you delegate its control to somebody else, accept the limitations on your own use this entails, hope it will not brake by mis-operation and you also get rewarded fairly for its services? This is what "traditional" methods require. Instead, you probably would rather prefer a scenario where

- the availability of (renewable) energy leads to a lower electricity price (reflecting the fact that LCOE of PV and wind is well below that of diesel electricity anywhere in the world),
- your device responds to such price changes automatically, by shifting operation to times where prices are lower (within the limitations you have set, and fully respecting the constraints of the functionality it provides for you),
- this provision of flexibility is reflected in a reduction of your electricity bill.

In addition to this individual benefit, the reduced need for storage investment on the system level reduces the cost that must be distributed and allocated to all grid users.

IV. CREATING REAL-TIME BALANCE PRICES BY CONTINOUS AUCTIONS

While mechanisms to introduce changing energy prices have been implemented in various countries, they have not been transferred yet to micro grids. Therefore, let us take a short excursion to economic and physical theory to show how better implementations are possible than the ones considered necessary today.

The purpose of changing energy prices is to balance generation and consumption. Leon Walras in the 19th century developed the concept of a "Walrasian Auction" where a neutral auctioneer collects the necessary information to achieve equilibrium - the price at which supply equals demand [2]. This traditionally is done by collecting "bids" from potential buyers and sellers. If we apply the same challenge to a micro grid and also remember and integrate some laws of physics (Kirchhoff's law, Maxwell's equations), the task of establishing the equilibrium price becomes much simpler [3]:

- If the previously published price was too high, production exceeds consumption and energy has to be exported.
- This fact can be detected instantaneously from grid physics and used to correct (in the example: reduce) the balance price relative to the previous one.
- In a continuously updated process, any existing imbalances will disappear after a few updates.
- Due to the fact that electromagnetic waves travel close to the speed of light, this "continuous approximation" can be done in seconds, and the established equilibrium price of the micro grid tracks the "real" one without relevant delay.
- Notice that this allows real-time or "closed-loop operation" and system stability provision through decentral flexibility.
- Also, as no "bidding" is necessary which implies that participants are not bound to "schedules", participation of many potentially flexible grid participants becomes much easier.

Micro grids typically have two modes of operation: They can be connected to other electrical systems via transmission or distribution grids. In that case, energy export can be detected by power flow at the connection point. Or they are fully isolated or temporarily operate in islanded mode. Energy cannot be exported out of an isolated system, but is absorbed by inertia and causes frequency drift.

Consequently, there always is a simple way to detect deviations from equilibrium and re-establish it according to the method described above: The only information required is power flow at the connection point in case of a connected grid, and frequency drift in case of isolated mode.

V. REFERENCE IMPLEMENTATION IN GERMANY

Initiated by citizen action to reduce their carbon footprint, a demo project (SoLAR Allensbach) has been implemented that uses the method described (chapter IV) to integrate existing flexibility to balance supply and demand. In a residential development, 12 heat pumps, a CHP unit, up to 24 EV chargers plus white goods (washing machines, dishwashers) co-operate - coordinated by a local market - to balance volatile local PV generation. The price signal is derived at the grid connection point of the community and distributed within the community through a local Ethernet network. Note that the demand on the performance of the communication infrastructure is very low: One byte per second being broadcasted is enough, and no signal return channel is required. Algorithms that change the operation time of individual appliances depending on their actual flexibility and community level price changes they receive have been implemented within the controllers of individual appliances (e.g. heat pump controllers) or centrally (where direct integration of algorithms into the appliances would have required higher budgets). Simulations done within the project suggest that just household fridges and freezers that shift the time when they switch “on” and “off” could provide a substantial share of the control power required by our energy systems today. This project has been selected for the “Good Practice Award of the Year 2021” [4] of the Renewables Grid Initiative. Its details have been presented at a conference [5].

Even if dynamic tariffs are not billed yet in the demo project, they increase self-consumption if flexibilities react to them. This creates added value by reducing the amount of energy that is exported to the external grid for a low feed-in tariff, which needs to be bought back at a different time at a higher purchase price. In the project example with a self-consumption rate of 50% without this technology, the expected rate with system co-ordination is 80% (an increase of 60% just from more efficient, flexible operation, and before the first integration of batteries). This creates a margin of some 5 ct/kWh at the community level which is distributed to the participants enabling it. Beyond this local optimization, grid load at the connection point is also reduced, which reduces grid extension needs. Adequate financial compensation for this grid-supportive effect is not considered yet in the demo, but would further increase the value for the community.

VI. TRANSFER OF APPROACH TO ISOLATED MICRO GRIDS

The technology and algorithms used in the demo project “SoLAR Allensbach” (Chapter V) can directly be transferred to other micro grids: If it is a connected micro grid, the technology can be transferred directly. There may be other communication channels or software/hardware environments used, but the logic is identical and has very low demands on their performance capabilities. In the case of isolated grids, grid frequency can be used alternatively to encode and transport the price signal. It can be received at any point in the grid with very low-cost components, and this communication channel cannot fail nor be manipulated by cyber-attacks. Most appliances today are controlled by one or more micro controllers. Using their quartz and serial input port, they can measure grid frequency, and their processing capabilities are also powerful enough to execute the load shifting algorithm.

Of course, in order to use demand side flexibility, you must first look for flexible loads that could be integrated. Water pumping (processing, desalination) and heating/cooling processes are usually very attractive and should be integrated in a first step. They already have a buffer (thermal or hydraulic), can be equipped with one, or the existing buffer size (determining flexibility) can be increased. The algorithm developed for the SoLAR project is designed to upgrade existing two-point controllers that are typically used in such applications. By adding such an algorithm, they can also consider price differentials and available temporal flexibility in their switching decisions. It is universal for different processes, self-learning, and can be integrated into existing control environments. There it adapts to existing and changing requirements by learning price and consumption patterns within a few days. Conventional and price-sensitive devices can be mixed in any ratio, and flexibility integration can be step by step as more and more flexible devices become available.

Of course, any other algorithm that translates price changes into time-shifted operation can be applied also.

The following points should be considered when integrating a real-time local market in an isolated micro grid:

- Set genset control to lowest speed (grid frequency) with maximum load, and highest at zero load (it will behave as inertia in the grid).
- Define an energy price coding for your micro grid to be lowest for maximum, and highest for minimum grid frequency. The highest price typically is determined by the LCOE of diesel electricity, the lowest typically is at or slightly below zero.
- Equip grid assets that should actively contribute their flexibility with price reception capability (frequency measurement and translation into energy price signal) and algorithms to optimize their energy cost or income position
    - Directly in the process controller or in an add-on device of loads or generators (CHP) that can shift operation time.
    - PV or wind generation assets should ramp down as prices become negative (reflecting their close to zero variable cost).

  - A reference algorithm to implement these functions can be supplied if desired.
- If dynamic prices not only are used for better coordination and lower systems cost, but also to financially reward individual contributions by actually billing them, a price receiver can be added to smart meters also. They then can weigh and store consumed (or produced) energy with the applicable price in the relevant period.

VII. OVERCOMING POTENTIAL BARRIERS

The introduction of new technology usually raises new questions. Here are some answers to typical ones we were asked:

- Do we need to change everything to introduce this capability? No, because the introduction can be step by step, with only some flexibilities being integrated in a first step, others following later.
- In our environment/regulation, there is no such thing as dynamic prices? The answer has two parts: First, dynamic prices create value by coordinating system participants better, even if they are not billed (as in SoLAR), so more renewables can be used with lower investment in storage. Second, there are many non-regulated applications (behind the meter, at commercial sites or in private grids) where application can start, to then convince regulators to enable their use at larger scale in regulated environments.
- Because of unbundling, our grid operator cannot be involved in market activities (creation of price signals)? The grid operator is not involved beyond enabling access to grid state information. It can provide existing data from its SCADA system or allow others to derive it from the grid themselves.
- We have no devices that can react to dynamic tariffs? This is normal because so far there was no need for flexibility and therefore no dynamic tariff to react on. Many energy-consuming devices have temporal flexibility, and in most cases, it is financially attractive to enable them to provide it (by upgrades or when investing in new equipment), as the value created exceeds complexity and cost of enabling it.

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