Integrating High Shares of Variable Renewable Energy in Costa Rica

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***Abstract*—Different from most European high-VRE countries, such as Denmark, Germany or Ireland, Costa Rica already generates almost all of its electrical energy from renewables, mostly hydroelectric generation. The Costa Rican hydro generation is highly dependent on weather patterns and most of its generation capacity during dry season is located in a rather small area. This may lead to challenges when integrating VRE that are much different from the much-studied European and North American cases. Therefore, Energynautics, DIgSILENT and Meister Consultants Group (MCG) have been commissioned in 2015 by the Inter-American Development Bank, the Costa Rican Ministry of Energy, MINAE, and the Costa Rican power utility ICE to conduct a wind and solar (variable renewable energy, VRE) integration study in the Costa Rican grid. Within the scope of the study, different scenarios with increased shares of VRE for 2018 and 2024 were simulated with an advanced model of the Costa Rican power system. Simulations included security constrained optimal power flow calculations for whole years, contingency analysis and steady state and dynamic grid stability analysis. This paper focuses on the impact of high shares of additional wind power on the Costa Rican system.**

Keywords: VRE integration,wind power, utility scale PV, distributed PV, hydro reservoir management, volatility, balancing, virtual power plant.

I. The Costa Rican Power System

The Costa Rican power system is a 60 Hz system with two transmission grid voltages, 230 kV and 138 kV. The underlying distribution system runs on 34.5 kV and 69 kV and uses a typical American layout with long medium voltage feeders and short, one-phase 120 V low voltage feeders to deliver electrical energy to the customer.

With 4.8 million inhabitants, the Costa Rican peak load is 1600 MW, yearly electricity demand was around 11 TWh in 2015. Grid access is very high at 99.3 %, with Costa Rica having the highest standard of living in all of Latin America, but per capita electricity use is moderately low (around 1900 kWh p.a.) due to the moderate climate and the lack of heavy industry. [1] All of the Costa Rican transmission system, around 80 % of the generation capacity and 80 % of the distribution grid are directly or indirectly owned by the state-owned utility company ICE (Instituto Costarricense de Electricidad), making Costa Rica a vertically integrated power system. Privately owned generation is allowed, with the share of such generation being limited to 30 % of overall installed capacity by law, and privately owned generators being limited to an installed capacity of 20 MW per unit. The respective departments of ICE release plans for generation and line expansion every two years.

Costa Rica generates most of its electricity from hydropower. Besides a significant share of pure run-of-river power plants, there are several hydro reservoirs with weekly or daily regulation, the most notable being the 883 MW "Main Cascade (see Figure 1)," a cascaded hydro scheme on the Macho and Reventazón rivers.

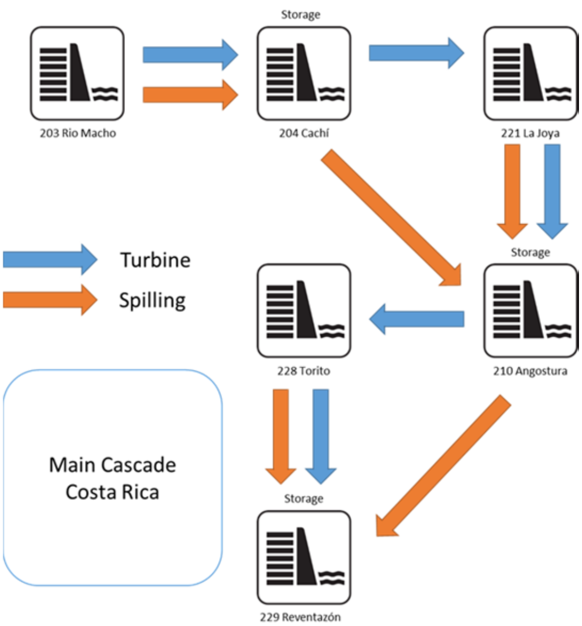

Figure 1: 883 MW cascaded hydro scheme on the Macho and Reventazón rivers.

Together with the smaller pondage schemes Toro and Garita/Ventanas and the larger Pirrís reservoir, a considerable amount of energy storage capacity is available in the Costa Rican system.

While small amounts of wind generation and bagasse-fired biomass power plants are used the whole year round, most of the power dispatch in Costa Rica depends heavily on the time of the year. During rainy season, run-of-river and smaller reservoirs provide baseload duties. Even curtailment of run-of-river generation by bypassing the turbines or spilling water from reservoirs is already common, as the system has to be dimensioned for the lower inflows of the dry season.

Whereas, during the dry season, the seasonal reservoir at Arenal, feeding the 370 MW ARDESA cascaded hydro scheme, which is filled by natural inflow during the rainy season, takes over a significant share of the baseload duties from run-of-river and smaller reservoirs. The latter are then used for intermediate load and peaking. During dry season, demand cannot be completely covered by renewable generation. The remaining demand is covered by geothermal power plants which provide around 15 % of yearly generation, and an increasing share of currently around 10 % of wind power. Depending on hydro availability, the use of oil-fired generation in the form of diesel-fired gas turbines and heavy oil fired medium-speed diesel power plants may also be necessary. Altogether, Costa Rica generates more than 90 % of its electricity from renewable resources, the exact share is highly dependent on the weather. [1]

The Costa Rican transmission grid mainly connects the cities of the Central Valley, where most of Costa Rica's population lives (see Figure 2), with the hydro and geothermal generation sites in the north and in the east, with the north eastern lowlands and the southern rural areas possessing no transmission lines (see Figure 2.) Costa Rica is interconnected to the Central American synchronous grid which stretches from Guatemala (with connection to the Mexican grid) to Panama. Costa Rica, located on a narrow part of the Central American land bridge, borders on Nicaragua in the North and Panama in the South, with one 230 kV line with a thermal capacity of 300 MW crossing each border. This line is part of the SIEPAC Central American Interconnection, a line that connects all countries between Mexico and Panama except for Belize. However, due to the structure of the power generation in Costa Rica and the neighboring countries, the use of the SIEPAC line for energy imports and exports is very limited. [2] The line is mostly used to transport energy from northern Costa Rica to the densely populated Central Valley which leaves little line capacity for additional imports or exports. Most Costa Rican wind and geothermal generation and a significant amount of hydro generation is located in the province of Guanacaste in northern Costa Rica (see Figure 2) and directly connected to the SIEPAC line.

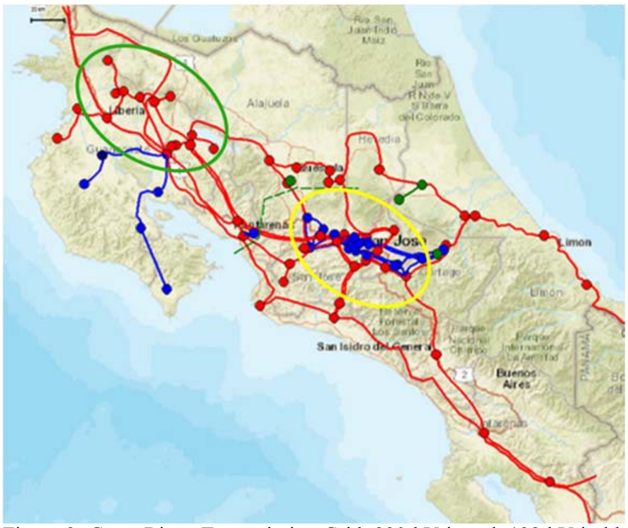

Figure 2: Costa Rican Transmission Grid, 230 kV in red, 138 kV in blue. The area in Guanacaste circled in green provides most of the generation during the dry season, while most of the load is located within the yellow circle.

II. VRE Generation in Costa Rica

A. *Current State of Wind Power in Costa Rica*

Wind power contributed 10 % of Costa Rican electricity production in 2015. Having installed the first wind turbines in 1996 already, Costa Rica was the first Central American country to introduce wind power. Currently, installed wind capacity amounts to 264 MW, almost all of which is connected in the north western province of Guanacaste, where average annual wind speeds is above 12 m/s on mountain ridges, and wind turbines reach yearly capacity factors between 40 and 50 %. Wind generation is generally higher during the dry season and mostly quite steady due to strong trade winds between the Atlantic and the Pacific Ocean.

Wind power is mostly privately owned and enjoys priority feed-in to ICE's single buyer system. For reasons of maintenance or grid congestion, each wind power plant can be disconnected for 72 hours each year by the utility without reimbursement. Grid code requirements still need some further development, but do already request low-voltage ride through (LVRT) and reactive power capabilities. At the current share of wind power, balancing of feed-in fluctuations is not a problem, as the Costa Rican fleet of hydro power plants displays a high degree of flexibility with both spinning and non-spinning reserves. For balancing within a longer time frame, the utility can react and correct the dispatch intra-day, unconstrained by any market mechanisms as the system is vertically integrated.

The share of wind power in Costa Rica is expected to increase due considerable investor interest in the good wind potential. An additional 190 MW of wind power are confirmed until 2019, with additional connection requests pending and additional capacities being considered in ICE's generation expansion plan until 2024.

B. *Current State of Solar Power in Costa Rica*

Due to high investment cost, solar power has so far not been used on a large scale in Costa Rica. Nevertheless, prices are dropping, and there is excellent solar potential in the country. PV has been utilized in some off-grid hybrid systems in the remote areas of the country to some extent, but the only centralized PV power plant connected to the Costa Rican power system is the 1 MW pilot project Solar Miravalles in Guanacaste. Privately owned, roof mounted distributed PV could not be connected to the grid until April 2016 because of legal issues. However, Costa Rica has recently introduced a net metering scheme for PV, making way for the connection of residential and commercial PV units to the distribution grids.

Costa Rican utility ICE is considering investments into solar power of their own, with some multi-megawatt scale centralized PV power plants in northern Costa Rica being currently under discussion.

C. *Expected System Impact of Higher VRE Shares*

The Costa Rican system is technically very well equipped to integrate high shares of VRE while maintaining a high degree of operational security. The transmission grid connections within the country are strong, already transferring high amounts of power from far-off generation to the load centers. Power plants are flexible and easily controllable, and reactive power reserves of the grid are high.

However, as Costa Rica already generates almost all of its electricity from renewable sources, the usual paradigm of replacing existing conventional generation with VRE as known from fossil fuel based power systems does not fully apply here. In the worst case, an increase of VRE capacity will not increase the share of renewable energy in the power sector, but merely replace power from other renewable sources such as hydro and geothermal. Thus, great care has to be taken in assessing the value of additional VRE generation from an economic and environmental point of view. The main benefits of VRE were identified to be the following:

- VRE could be used to reduce dependence on oil fired backup generation during the dry season and/or very dry years.
- VRE could help to maintain a high share of renewable energy as demand rises, allowing to postpone construction of new large hydro projects or an increase in thermal generation.
- VRE are modular, allowing for flexible addition of generation capacity and easier reaction to changing economic environments.

While within the Costa Rica VRE integration project high shares of both wind and solar power were analyzed, this paper will be focused on the impact of wind power.

III. Scope and Methodology of the Study

A. *Goals*

The study this paper is based on was commissioned in 2015 by the Inter-American Development Bank, Costa Rican utility ICE and the Costa Rican Ministry of the Environment and Energy MINAE to a consortium consisting of Energynautics GmbH (Germany), DigSILENT GmbH (Germany) and Meister Consultants Group (USA). The study is split into two phases: In the first project phase, it was evaluated whether some additional VRE installations can be added on top of the planned new generation capacities to be installed until 2018 without compromising system stability. The purpose of the second project phase was to analyze regarding the technic preconditions of the Costa Rican power system for absorbing high shares of VRE generation in 2024 . The identification of technical barriers, if existent, and the high level development of solutions to those was a central point of the work. This paper focuses on results from the second phase of the study, a technical analysis of a scenario for the year 2024 with very high shares of wind and solar power.

B. *Scope of work*

The scope of the technical evaluation is summarized in the following:

- Setup of a full AC grid model for steady state and dynamic analysis in DIgSILENT PowerFactory, the model was developed based on a PSS/E model and additional information provided by ICE;
- Setup of a power plant dispatch model based on information provided by ICE, including an SDDP database with historical hydrology data, and additional wind and solar time series obtained by the consultants through the REatlas program of Aarhus University, Denmark;
- Dispatch simulation based on a linear, (n-2) secure Security Constrained Optimal Power Flow in the grid optimization software ENAplan, yearly in 15-minute resolution, with three different hydrology and weather data sets for each scenario (dry, average and wet year).,
- Evaluation of generated energy per technology, VRE and hydro curtailment and reserve adequacy;
- Selection of critical dispatch situations and export of those into DIgSILENT PowerFactory for full AC simulations;
- Analysis of load flow, grid loading, voltage profiles, steady state contingencies and dynamic stability in DIgSILENT PowerFactory.

The stability of the Costa Rican power system was investigated for the horizon 2024 in order to verify compliance with the planning and operation security criteria in [3]. While the analysis did also include the assessment of transient rotor angle stability of the synchronous generators, this is influenced only marginally by the increased VRE generation, so that special attention is drawn here to the voltage and frequency stability.

C. *Weather data*

To account for the strong impact of weather patterns on the primarily hydro- and VRE based generation in Costa Rica, simulations were conducted using historical weather data from three different years:

- Dry year with low VRE availability as worst case, with data from 1994;
- Average year with high VRE availability with data from 1990;
- Wet year with moderately high VRE availability with data from 2002.

Hydrology data was provided by ICE, wind and solar data was obtained to the Renewable Energy Atlas program of Aarhus University and were based on satellite reanalysis and topology data.

D. Generator dispatch modelling

The model of the Costa Rican system required to conduct the described studies includes a full AC model of the Costa Rican transmission grid and all generator models, configured for steady state and dynamic analysis, and a generator dispatch model based on a linearized security-constrained optimal power flow (DC-SCOPF.)

The general workflow was an iterative two-stage approach, with DC dispatch model results being loaded into PowerFactory for full AC analysis, and additional constraints being added to the dispatch model afterwards for recalculation, if necessary. The DC-SCOPF model turned out to be so robust and the controllability of the Costa Rican system is so good that only very few iterations were needed in the end. Final results were obtained by loading the generator dispatch of 15 selected critical situations into the AC model and running the full set of steady state and dynamic stability calculations with them.

The development of the DC-SCOPF model focused on optimization of use of hydro reservoir capacities and their interaction with VRE, while keeping the system (n-2) secure even during situations with transfer flows of up to 100 MW through the country. Generation costs were set based on a merit order provided by ICE. Wind, solar and run-of-river hydro were given availability time series based on historical hydrology data and satellite reanalysis data. Hydro reservoirs were modelled with reservoir size and natural inflows from historical data. Cascading of hydro schemes was modelled according to topology and historical hydrology data provided by ICE.

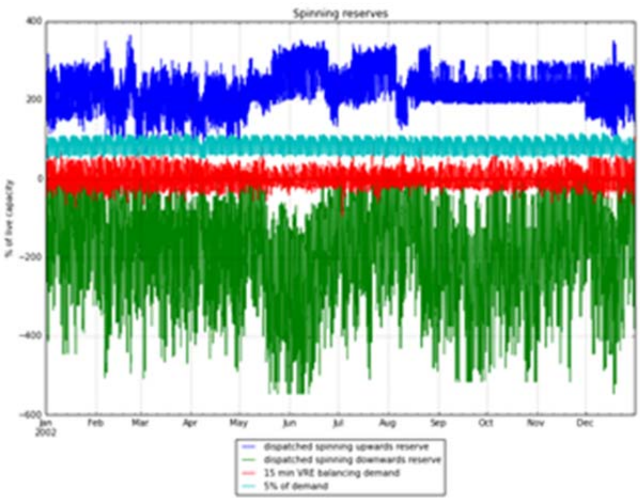

Figure 3: Dispatched reserve power and VRE fluctuations across one year, simulation result.

To account for daily regulation of smaller reservoirs, which make up a large part of Costa Rica's generation capacity, dispatch optimization was done for each 96 15-minute time steps of each day at once. Reservoir power plants were constrained with their inflows, reservoir sizes and reference levels (70 % at 00:00 for small reservoirs, yearly reference curves for large reservoirs.) Reservoirs were allowed to be drawn below their reference levels as a last measure if demand could not be covered otherwise.

The SCOPF functionality dispatches generation to match the load while keeping line loading at a level where a defined set of single and double line contingencies would not lead to any line overloadings, considering emergency line ratings in multiple contingency cases. As a number of hydro generators in Costa Rica are spinning as synchronous condensers to provide reactive power when they are not dispatched for active power, no additional constraints had to be set for reactive power provision. Reactive power flows, which the DC load flow inherently neglects, were accounted for by an additional safety margin on line loading. Spinning reserves were modelled by setting a number of hydro generators to must run dispatch[1] and reserving active power margins on all generators capable of providing reserves. ICE requires a minimum reserve of 5 % of total generation, but usually has more than that available due to load following hydro generators being run at below their rated output.

E. Model for dynamic stability analysis

An adequate representation of the VRE generation is of crucial importance for the quality of the simulation results so that considerable effort was put in the modelling aspects.

Wind and PV generation currently installed in Costa Rica and new plants under construction with commissioning date until 2018 totalize 372 MW of utility scale VRE generation directly connected at the transmission level of 230kV or 138kV. Their technical characteristics are known with reasonable accuracy. Therefore, these plants were added to the simulation model, partially as manufacture-specific models, where available, or via generic models per generation technology; i.e. fixed speed induction generators, induction generators with variable rotor resistance, and doubly-fed induction generators. Generic models were customized according to the expected response of the plant. For the older ones, this did mostly mean some limited fault ride-through capability.

New VRE generation for the horizon 2024 was exclusively modelled based on fully-rated converter technology. Even though doubly-fed induction generation is also likely to be built, this technology can provide similar dynamic support to the system stability as fully-rated converter generation does. Hence, for a bulk power system stability analysis, this modelling assumption is considered acceptable.

Both utility-scale and distributed VRE generation shall minimally remain connected to the system during frequency and voltage excursions resulting from simple and multiple contingencies as defined in [3]. Hence, in terms of simulation, all new wind/pv models included protection characteristics that allow operation, i.e. to remain connected, for the lower voltage-against-time profile and the maximum frequency excursions defined in [3].

Of particular importance is the technical capability assumed for new utility-scale VRE generation to support the dynamic stability of the system. The models used for

[1] Only during times where hydro inflows would allow continuous operation.

simulation were defined in line with requirements for Type-C plants in [4], featuring the following characteristics:

- Voltage regulation at the point of common coupling (PCC): Opposite to the existing plants operating at constant power factor, future VRE generation shall actively participate in the voltage control providing reactive power to the system and countermeasure the loss of reactive power reserve due to displacement of synchronous-based generation
- Over-frequency sensitive mode: VRE generation is able to provide active power frequency response with a gradient of active power reduction of 50%/Hz for the system frequency above 60.2Hz
- Dynamic voltage support capability: A VRE generator can support the network voltage by means of additional reactive power. The reactive power injection is activated in the event of a voltage drop of more than 10 % of the effective value up to a maximum of 100% of the rated current of the converter.

IV. Scenario Development

A. Installed Capacities

For the 2024 scenario to be simulated, the energy demand increase between 2018 and 2024 should be covered completely by VRE and the new geothermal unit Pailas 2, which is already under construction.

- According to the projection agreed on with ICE, demand is expected to rise from 11,657 GWh in 2018 to 15,041 GWh in 2024, an increase of 3,384 GWh or 29 %.
- 485 GWh can potentially be produced by Pailas 2, leaving 2,899 GWh to be produced by additional VRE units.
- Assuming capacity factors of on average 42 % for wind and 17 % for solar, this would require at least 785 MW of new wind capacity, or 1946 MW of PV capacity, if only one technology is to be used.

Before determining the optimal distribution of wind and solar installations, the best combination of wind and solar had to be found. . Therefore, different possible combinations of wind and PV were simulated in yearly runs for a sensitivity analysis with the full dispatch model, but with very relaxed grid constraints (100% thermal capacity of all lines available, no (n-1) security).

The favored scenario for 2024, which all subsequent calculations were based on, is the one with 470 MW additional wind and 790 MW additional PV. Overall installed VRE capacity is 52 % wind (842.75 MW) and 48 % PV (790 MW) Installed capacities in Costa Rica for the considered 2024 Advanced VRE scenario by VRE technology are displayed in Table 1.

Table 1: Installed VRE capacities ind 2015, expected for 2018, and of the 2024 VRE Advanced Scenario.

	2015	2018 Base	2024 Adv.
Wind	264 MW	373 MW	843 MW
Centralized PV	1 MW	1 MW	391 MW
Distributed PV	0 MW	0 MW	399 MW

B. Distribution of Installed Capacity

Installed capacity of both wind and centralized solar was distributed within Costa Rica with the goal of making optimal use of resources without making any grid reinforcements beyond the projects confirmed by ICE until 2024 necessary. The total VRE capacities to be additionally installed were split into 5 wind farms of 94 MW each and 10 PV plants with 39 MW each. Starting out with distributing both types of VRE to the highest potential locations, capacities were then redistributed to second-rate locations step by step if violations of grid constraints occurred.

1) Wind

Contingency security, especially in the Northern Ring area, was the main driver behind the redistribution of wind power and the setup of the final scenario. Locating all five wind parks to the best five nodes, which are all in the Northern Ring in Guanacaste, lines in the Northern Ring were loaded by up to 110 % during single contingencies and up to 150 % during double contingencies. The most critical case is a high wind, peak load situation during the wet season of a wet year (see Figure 4). Using curtailment for line relief leads to barely acceptable 4 % of overall yearly wind curtailment when respecting (n-1) security, and an inacceptable almost 20 % if (n-2) security has to be kept, which is one of ICE's operational security requirements.

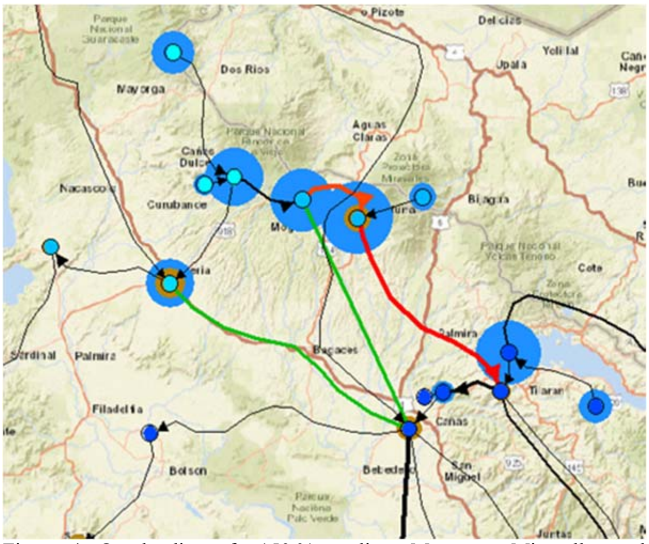

Figure 4: Overloading of >150 % on lines Mogote – Miravalles and Miravalles – Arenal (shown in red) in case of a double contingency and 470 MW of additional wind installed at the five best wind locations.

If wind was to be connected at the best locations, a second circuit throughout the entire Northern Ring, amounting to 200 km of new 230 kV circuit, would be necessary, despite the already reinforced lines. Almost the entire 300 MW of wind power existing in 2018 will be connected in the area already. Around 220 MW of additional wind can be integrated in Guanacaste without excessive curtailment or grid expansion and without compromising (n-2) security.

Considering transfers on the SIEPAC line are expected to rise as regional market integration commences, only two of the five new wind parks were connected to the Northern Ring, feeding 94 MW each into the substations at Liberia and Corobici while tapping the best possible wind resources in the region. The remaining wind plants were moved to second-rate locations elsewhere in the country, mostly close to the Central Valley, sacrificing a few per cent of yearly capacity factor for better grid integration.

2) PV

The best solar potential in Costa Rica is found in western Guanacaste and on the Nicoya peninsula, but as these areas connect to the Northern Ring of the Costa Rican grid where a most of the wind power is installed, only 156 MW of PV could be connected without either frequently violating grid constraints or getting unacceptably high curtailment. The rest of the capacity was distributed to Jacó on the Pacific coast and along the southern Atlantic coast. The latter locations are definitely second rate for Costa Rica, but with an average yearly irradiation of 1700 – 1900 kWh/m3 still more than acceptable. These locations were chosen after wind and distributed solar had been distributed because they had the highest energy yield, other locations with more potential had more limited grid capacity.

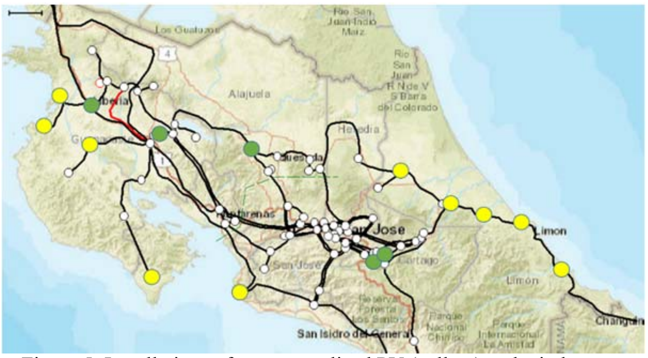

Figure 5: Installations of new centralized PV (yellow) and wind power plants (green) for the 2024 VRE Advanced scenario.

V. Results

A. Impact of VRE on generator dispatch

The results for the 2024 simulations show that increased VRE shares lead to a considerably lower utilization of expensive and polluting thermal generation, but also impacts the operation of other renewable generation such as hydro and geothermal power. This means that covering the additional electricity demand between 2018 and 2024 comes at the cost of displacing other renewable sources with VRE, freeing considerable generation capacities for electricity export in the wet season.

From the amount of generation that is displaced by VRE, which was obtained by comparing results from the 2024 VRE Advanced scenario to simulation results from a scenario without any additional VRE beyond 2018, the conclusion can be drawn that VRE are most beneficial during very dry years (see Table 2).

Table 2: Yearly energy displaced by VRE feed-in per technology.

Weather year	Dry (1994)		Average (1990)		Wet (2002)	
	GWh	***%***	***GWh***	***%***	***GWh***	***%***
Displaced thermal	1029	56	462	60	351	72
Displaced RoR	105	3	211	6	283	7
Displaced reservoir	829	15	1312	21	1455	24
Displaced ARDESA	45	3	491	37	578	45

A large part of thermal generation is displaced, thermal generation is reduced by 60 % across all weather years.In absolute terms, the reduction is greatest during a dry year. During the years with higher hydro availability, more hydro is replaced, while a small share of thermal generation always remains. This may be acceptable if excess hydro power can be sold to the regional market, otherwise, the economic feasibility of such high VRE shares in a system already highly dependent on renewables is determined by fuel prices and national CO2 targets.

B. Grid impact during steady state operation

Due to the security margins that are required to be kept on lines and transformers for (n-1) and (n-2) security and the high degree of redundancy present, element loading in the high voltage grid is low. During regular operation, lines do not exceed 50 % of their thermal capacity. Compared with the DC load flow for the dispatch optimization, results are very similar because reactive power is mostly supplied locally and reactive power flows are low. The grid itself does not require high charging currents either. The voltage control capabilities of the Costa Rican transmission grid are outstanding, with multiple large generators being able to run in synchronous condenser mode when not dispatched for active power, and compensation assets at critical high voltage busbars, supported by condenser banks in many 34.5 kV substations with high load. Thus, voltage problems are very limited even at high VRE penetrations. Even with all non-generation compensation assets switched off, voltage was within the allowed range for all normal operation cases.

Voltage in the Costa Rican transmission grid must be kept between 0.95 and 1.05 p.u. at any point at any time during normal operation as well as in single contingency cases. In case of a multiple contingency, this range is doubled, voltages between 0.90 and 1.10 p.u. being allowed.

The SCOPF used to optimize the power plant dispatch already considers all critical line outages. The full AC contingency analysis, using the contingency tool of DIgSILENT PowerFactory, is thus mostly necessary to check the quality of the SCOPF. Moreover, some additional transformer and busbar outages are considered that are not part of the DC SCOPF, and all cases are checked for voltage deviations which cannot be done in ENAplan. Voltage can be kept between 0.95 and 1.05 p.u. for single and between 0.09 and 1.10 p.u. for multiple contingencies at all substations in all situations. No curtailment is necessary for any of the scenario years without transfer flows. Keeping margins on the lines for a 100 MW flow from north to south leads to 1.6 % of yearly curtailed wind energy which is acceptable. Line loadings even in double contingency cases never exceed 85 %.

Figure 6: Results for wet year, wet season, high wind / peak load: No overloaded lines, highest loadings occur on the lines Mogote – Canas and Rio Macho – Cachi during double contingencies in the respective areas.

C. *Dynamic stability*

Simulations results of simple, double and bus bar 3-phase faults for the numerous operation scenarios showed that the system can operate secure and stable for the level of VRE penetration proposed for the horizon 2024. The operation scenarios for the stability analysis were derived from the year round generation dispatch simulation described in Section III.D and aimed at maximizing the instantaneous penetration of VRE generation, reaching penetration levels of 60% of demand as shown in Table 3 for some selected scenarios.

TABLE 3: SELECTED DISPATCH SCENARIOS FOR THE STABILITY ANALYSIS

	WET Season		DRY Season	
	PEAK (Day)	***MIN***	***PEAK (Day)***	***MIN***
Synchronous Generation(MW)	641.4	413.5	771.1	293.6
Wind Generation (MW)	762.2	755.1	761.0	758.7
PV Generation Large Scale (MW)	292.3	0.0	292.3	0.0
PV Generation Distributed (MW)	300.0	0.0	300.0	0.0
Other Generation (MW)	265.7	14.9	145.5	135.6
Total Generation (MW)	2261.5	1183.5	2269.9	1188.0
Demand (MW)	2232.0	1165.0	2232.0	1165.0
Losses (MW)	30.3	18.5	37.9	23.0
VRE Penetration (% demand)	60.7	64.8	60.6	65.1
Spinning Reserve (% demand)	13.4	7.5	12.8	7.9

1) *Voltage Stability*

In contrast to the current concentration of VRE generation in the Northern part of the country, the geographical distribution proposed in the VRE scenario 2024 noticeably improves the voltage stability in critical areas of the system, as far as it better distributes reactive power reserves across the system.

For the various operation scenarios, the study assessed the maximum reactive power step changes in all generators performing voltage control for every contingency. In all cases, an increase of the reactive power contribution from VRE generation was observed. As for illustration purposes, VRE generation contributes with around 40% (82 Mvar) of the total reactive power increase following the critical bus bar fault at Garabito 230 kV in the peak (day) situation for the dry season. For the same fault, the Q-V curve in Figure 7 shows that reactive power margin at the strategic bus bar Lindora 230 kV (close to the demand center in the Central Valley) is of around 367 Mvar and 496 Mvar with reference to the minimum operation voltage (0.9 pu for bus bar faults) and the voltage collapse, respectively. These margins are well above the minimum security margins currently used for the planning and operation of the system. Similar behavior was observed in the other scenarios and contingencies considered in the study.

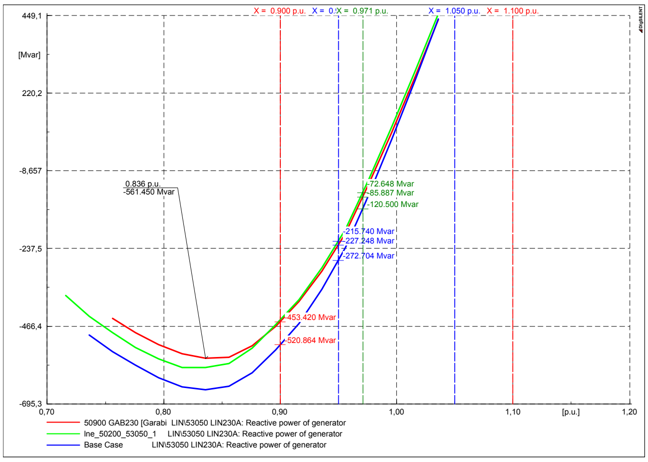

Figure 7: Q-V curve at bus bar Lindora 230kV for the base case (n-0) and the critical contingencies Garabito 230kV (bus bar fault) and 230kV line Lindora-Arenal under peak (day) demand in the dry season

In terms of short-term voltage stability, the simulations showed that no cascade disconnection of generation is to be expected and that the voltage at all major 138 and 230 kV bus bars dynamically recovers within the allowable limits.

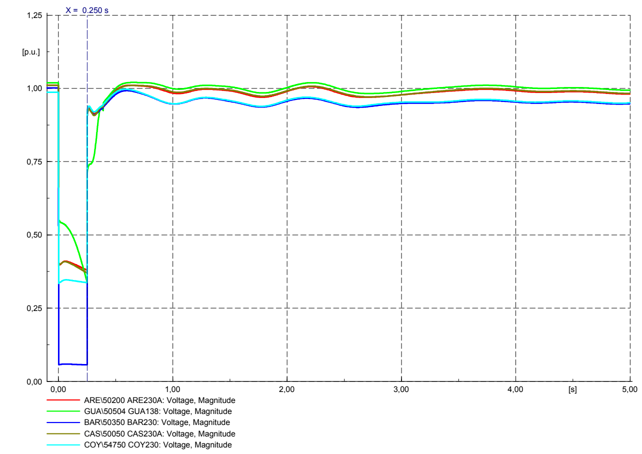

Figure 8: Dynamic voltage recovery after a bus bar fault at Garabito 230kV for peak (day) demand in the dry season.

2) *Frequency Stability*

The frequency stability analysis underlies the assumption that the Costa Rican system operates isolated from the interconnected Centro American system, i.e. from Nicaragua in the north and Panamá in the south. Whilst the assumption is very conservative, it did happen several times in the past and cannot be discarded in a near future. Hence, for the purpose of the analysis the primary frequency regulation relies on the generation and demand side management in Costa Rica only.

VRE generation is not expected to provide active power frequency control during under-frequency conditions. While technically possible, it would require dispatching VRE generation below the available wind or pv resources, which is economically not desirable. At the same time, VRE generation displaces conventional synchronous generation and consequently reduces total system inertia, which in turns impacts the frequency stability of the system. The level of spinning reserve is maintained around the current level of at least 5% of the demand.

For all simulated cases in the 2024 scenario, the frequency in the isolated Costa Rican system remains stable after the loss of the major block of conventional generation, i.e. the loss of the major power plant following a fault in the associated 138 or 230 kV bus bar. As a worst case, the sudden loss of 110 MW in Pirrís 230 kV results in a total load shedding of around 66 MW with the frequency stabilizing at a residual deviation of 110 mHz. The rate of change of frequency is of about -300 mHz/s. It should be noted that the load shedding scheme was not reviewed within the scope of work of this study and the current scheme was used in the simulations.

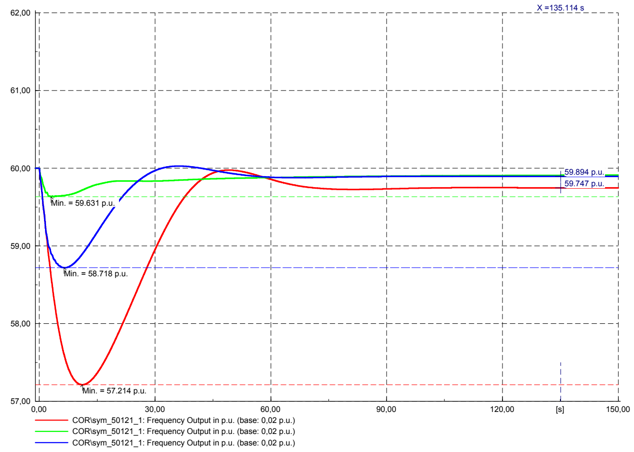

Figure 9: Primary frequency response for the loss of 110MW of generation in Pirrís. In Green: Costan Rican system interconnected to the SIEPAC; in Blue: isolated operation with a total load shedding of 66MW, in Red: isolated operation (without load shedding scheme.)

It is envisaged that a major regional integration will reduce the amount of necessary primary reserves in the system – and the cost, as well as it will increase the frequency stability of the system.

VI. Conclusion

The Costa Rican system is technically well equipped to absorb high VRE shares without any operational security problems. No additional grid reinforcements necessary if VRE generation capacity is distributed as outlined in the scenario, but a small amount of allowed VRE curtailment is a valuable tool in VRE integration. Distributing VRE installations throughout the country instead of concentrating them in Guanacaste reduces loading on the grid and facilitates balancing, relieving operating reserves. With a wide-spread distribution across the country, high shares of wind with instantaneous penetration rates of up to 70 % of the load can be realized without endangering the stability of the system. Due to the good controllability of the generators and the strength of the Costa Rican grid, voltage and frequency can be kept stable at all time. Prerequisite for this is the implementation of an updated grid code which requires wind power plants and utility scale PV installations to provide advanced fault ride through capabilities with dynamic reactive power control. More advanced options, such as delta controlled operation of VRE units and active frequency control, are not strictly necessary, but may increase the controllability of the system even further.

VII. Sources

[1] I. Erlich, G. Krost and M. Wilch, "Wind Integration into the Costa Rican Power Grid," Institute of Electrical Power Systems, University Duisburg-Essen, Duisburg / Essen, Germany, 2010.

[2] Centro Regional de Coordinacion de Transacciones - ENTE Operador Regional, "enteoperador.org," 10 September 2015. [Online]. Available: http://www.enteoperador.org/newsite/flash/SER.html. [Accessed 10 September 2015].

[3] Comité Técnico de Seguridad en la Planificación, Diseño y Operación del SEN, „Criterios de Seguridad para la Planificación, Diseño y Operación del Sistema Eléctrico Nacional,“ Instituto Costarricense de Electricidad, San José, Costa Rica, 2003.

[4] ENTSO-E (www.entsoe.eu), „Network Code for Requirements for Grid Connection Applicable to all Generators,“ ENTSO-E, Brussels (Belgium), 2012.

[5] Instituto Costarricense de Electricidad, "Plan de Expansión de la Transmisión 2013 - 2024," ICE, San Jose, 2013.

[6] Instituto Costarricense de Electricidad, "Plan de expansion de la generacion electrica - Preiodo 2014-2035," ICE, San Jose, 2014.

[7] E. Tarbuck, "The Argentina Independent," 17 May 2013. [Online]. Available: http://www.argentinaindependent.com/currentaffairs/newsfromlatinamerica/nama-regional-support-provides-relief-from-energy-crisis/. [Accessed 11 September 2015].