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Energy Supply on Interconnected Renewable Based Islands in the Eastern Caribbean Sea

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I. Introduction

Today's energy supply on eastern Caribbean islands is mostly based on diesel and oil fired power plants [1]. This leads to relatively high electricity cost, CO_2 emissions and dependence on fuel imports [2]. Good natural weather conditions and a large geothermal energy potential on several islands enable electricity supply by renewable energy sources (RES) [3–5]. Previous work has shown potential to reduce cost and greenhouse gas emissions by substituting fossil power generation with RES [6]. Further savings are expected by interconnecting several islands with undersea cables. This work analyses the economic benefits of interconnected islands taking the example of four eastern Caribbean islands: St. Vincent, Grenada, St. Lucia and Barbados. Figure 1 shows the investigated islands with possible minimum-distance routes for the transmission lines.

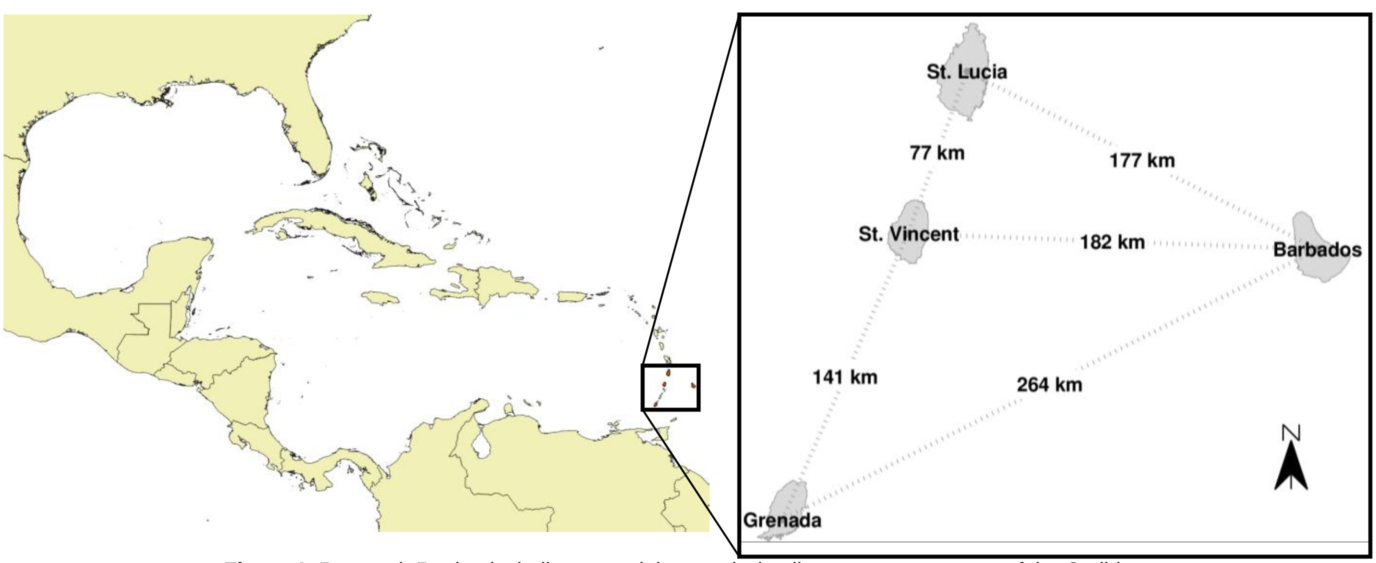

Figure 1. Research Region including potential transmission lines as a map extract of the Caribbean.

A. *Purpose*

The objective of this work is to investigate the techo-economic potential of electrical interconnection of islands energy systems regarding the integration of RES. It will be analyzed if the storage demand of individual islands, caused by large implementation of volatile energy sources, can be reduced by interconnecting islands. Furthermore geothermal power supply on Barbados via an electrical interconnection from Grenada, St. Lucia or St. Vincent will be investigated. This work deals with the tradeoff between storages and grid in terms of grid integration of renewable energy sources.

B. Approach

In order to evaluate the cost-optimal energy supply option an extended energy system is considered. It consists of the current fossil power plants, wind energy, photovoltaics (PV), geothermal power and two storage options (see Figure 2). Furthermore electrical interconnections between the islands are assumed whose economic viability will be analyzed.

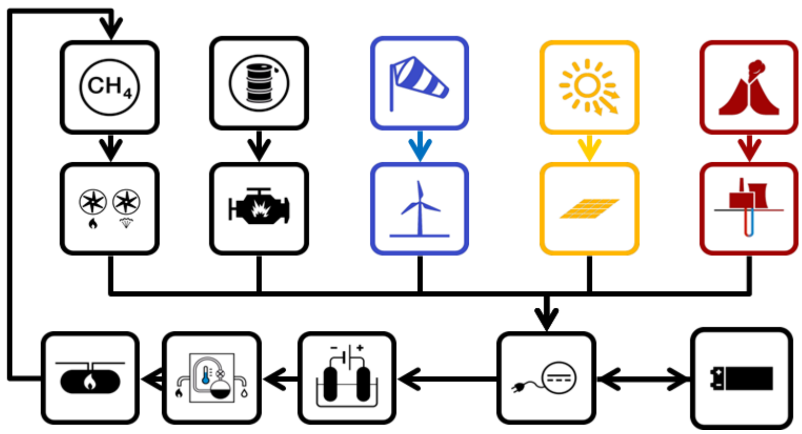

Figure 2 The proposed energy system consists of the current fossil power plants, wind energy, photovoltaics, geothermal power and two storage technologies: Batteries for short term power balancing and renewable power methane (RPM) as mid and long term storage. The RPM storage consists of electrolyzer, methanation unit, gas storage and a combined cycle gas turbine.

In this work several scenarios will be investigated. The reference case is the energy supply situation of today where electrical energy is mostly supplied by diesel fired power plants. The first scenario is energy supply without electrical interconnection of islands: One case with only photovoltaics, wind energy as renewable energy sources and existing diesel gensets as balancing power plants. In the second case this system will be supplemented by geothermal power. The above described scenario will be compared with two interconnection scenarios: One without and the other one with the use of geothermal power.

II. Methods

The analysis is performed by simulating one year's electricity supply based on given load profiles. A multi-region model describes the electrical energy system including the transmission lines. The energy supply is formulated as mathematical optimization problem aiming at least cost electricity under the constraint of meeting the demand on each island in every hour of the year.

A. Energy System Model

In order to evaluate the competitiveness of renewable power plants a techno-economic model is used. This model roughly describes the physics of the energy system: Each island is represented as one region wherein the distribution grid is neglected. The outputs of the model are a cost optimized energy system, the hourly power plant dispatch and the annual system costs. The optimal system configuration, including spatial allocation of generation capacities, relies on investment decisions which are made in a period of one year. Equation 1 depicts the objective function whose value will be minimized during the optimization. In words: The total cost of power generation, storage of energy and power transmission will be minimized.

$$min\sum_{r}\sum_{i}\left(\left(Capex\left(r,i\right)\cdot CRF\left(i\right)+Opex_{fix}\left(r,i\right)\right)\cdot Cap\left(r,i\right)+\sum_{t}Opex_{var}\left(r,i,t\right)\cdot E_{gen}\left(r,i,t\right)\right) \quad (1)$$

Cost of power plants are represented by three terms: Capital expenditure (*Capex*), fixed (annual) operational expenditure ($Opex_{fix}$) and variable operational expenditure ($Opex_{var}$). The capital recovery factor (*CRF*) is described in the following section. The capacity of newly installed power plants is represented by *Cap* and the annual generated energy by E_{gen}. Index *r* represents the set of regions, *i* is the index for types of power plants and index *t* describes the time steps.

Equation 2 depicts the main constraint, which ensures demand satisfaction in each time step. In each node *r* and in each time step *t* the sum of generated (E_{gen}) or transmitted (E_{trans}) power has to equal the demand (E_{demand}). The term of storage power ($E_{storage}$) includes storage charge and discharge power. In case of oversupply the equation is balanced be the term excess power (E_{excess}).

$$\sum_{i}\left(E_{gen}\left(r,i,t\right)+E_{storage}\left(r,i,t\right)\right)+E_{trans}\left(r,t\right)-E_{excess}\left(r,t\right)=E_{demand}\left(r,t\right) \quad (2)$$

B. *Levelized Cost of Electricity*

During the simulation the energy supply including power plant investment is economically optimized. This requires a comparison of electricity cost from different power plants. The levelized cost of electricity (*LCOE*) offer a way of comparing electricity production cost by generated unit [7].

$$LCOE=\sum_{c}\left(\frac{Capex_{c}\cdot CRF_{c}+Opex_{fix,c}}{FLh_{c}}+Opex_{var,c}\right) \quad (3)$$

The LCOE are calculated by the capital expenditure, which is annualized by the capital recovery factor, the fixed and variable operational expenditures and the full load hours (*FLh*) of each component of the energy system. The *CRF* respects the cost of capital (weighted average cost of capital [*WACC*]) and the expected lifetime (*n*) of a component (index *c*).

$$CRF=\frac{WACC\cdot\left(1+WACC\right)^{n}}{\left(1+WACC\right)^{n}-1} \quad (4)$$

The costs for investments in the transmission grid are calculated according to the calculation for power plants and storages. The cost are equally assigned to the importing and exporting region.

C. *Data*

Disregarding of physical and financial parameters (which described in sec. Assumptions and being valid for investments in the year 2012) most important input data for the simulation are demand, irradiance and wind speed data. Historical demand data in hourly resolution from the year 2010, which are provided by the electricity utilities, are used in this work. Wind energy and PV feed-in data based on meteorological data, provided by the NASA, were already computed to electrical feed-in data in previous work [8]. The technical potential of geothermal energy was estimated by Josef et al. [5].

III. Results

The current electricity supply on the considered Caribbean islands represents the reference case with electricity generation only from diesel gensets. The average LCOE in this scenario adds up to 0.24 USD/kWh.

A. *Optimized supply systems without interconnection*

The cost-optimal energy system for investment costs of the year 2012 without transmission lines between the islands and excluding geothermal power leads to average LCOE of 0.098 USD/kWh. The RES penetration reaches 67 % with wind energy as the dominating energy source. Photovoltaic plays a minor role in energy supply; 13 MW of

PV are installed on St. Lucia (see Figure 3 a). Adding geothermal power to the system leads to overall LCOE of 0.085 USD/kWh for a RES penetration of 78,6 %. Local LCOE vary significantly, depending on the available energy resources on the island (see Figure 3 b). If geothermal power is available on an island it turns out to be the preferred energy resource. Due to extensive use of geothermal power on Grenada, St. Lucia and St. Vincent local LCOE on these islands adds up to two-thirds the cost of electricity on Barbados.

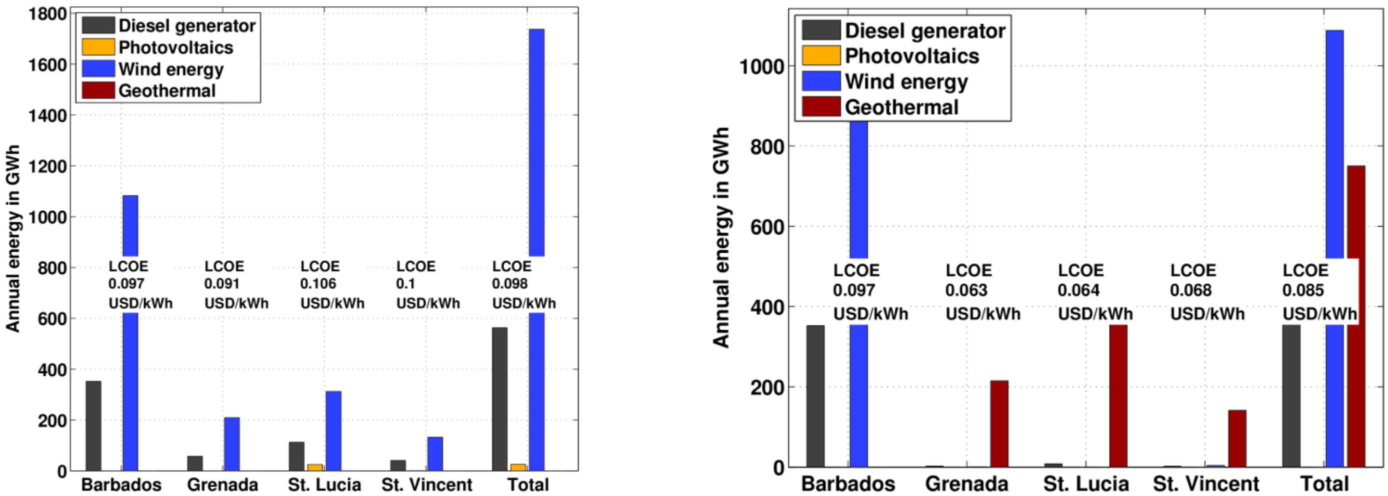

Figure 3 Annual energy generation of wind energy, PV, geothermal and diesel gensets. The LCOE are given as average LCOE for the energy systems of all four islands and as local LCOE for each island. The figure on the left hand side (a) is related to the non-geothermal scenario. The figure on the right hand side (b) shows the results for the scenario containing geothermal power.

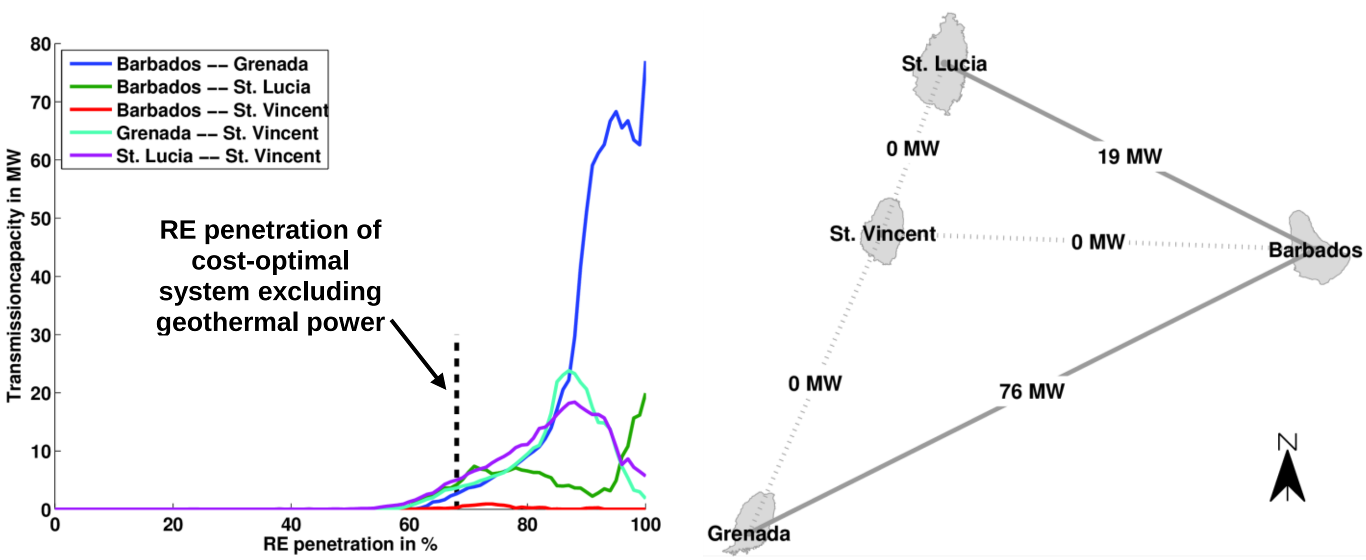

Figure 4 Left (a): Transmission need between pairs of islands plotted against the renewable electricity share. Transmission need between Barbados and Grenada significantly increases at renewable electricity shares higher than 80 %. Right (b): Necessary transmission capacities in a full RES supply scenario excluding geothermal power. The differences of transmission capacities in figure a and b result from limitations to two transmission lines with higher capacities.

B. Optimized supply system with interconnection

Cost-optimal supply scenarios excluding geothermal power generation do not incorporate economic viable interconnections between islands. At the point of cost-optimal renewable electricity share the largest transmission need adds up to almost 5 MW (see Figure 4 a). At a penetration of 100 % renewable energies a significant need of power transmission arises. A feasible scenario is Barbados connected to St. Lucia with a 19 MW transmission line and connected to Grenada with 76 MW transmission line (see Figure 4 b). With this full RES energy supply scenarios relatively high average LCOE of 0.144 USD/kWh could be achieved. However this 100 % RES scenario is 40 % lower in cost than the current fossil fuel based power supply.

Considering geothermal power as additional energy source enables the utilization of at least one economic viable interconnection. As shown before in the geothermal non-interconnection scenario geothermal power generation lowers the LCOE significantly. At a share of 98 % renewable power generation energy is predominantly supplied by geothermal power plants. In this scenario the average LCOE adds up to 0.068 USD/kWh (see Figure 5 a). A full RES energy supply can be achieved with slightly higher average LCOE of 0.073 USD/kWh (see Figure 5 b). The increased cost compared to the 98 % scenario results from higher excess production of geothermal power plants.

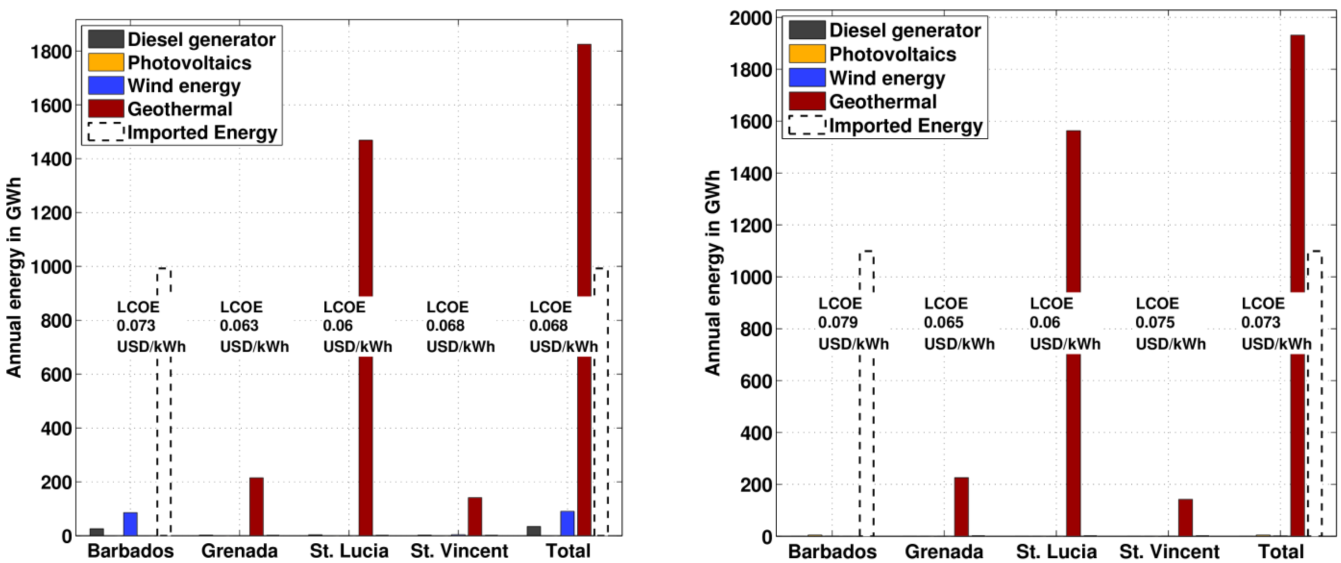

Figure 5 Annual energy generation and LCOE on each island respectively for all islands (Total). Left (a): Energy supply is mostly based on geothermal power. Most of Barbados' energy demand is supplied by geothermal power plants from St. Lucia. Wind energy serves a small amount and diesel gensets supply balancing power which adds up to 2 % of total energy generation. Right (b): A 100 % energy generation from renewable sources which is dominated by geothermal power. Only on Barbados 4 GWh are supplied by PV.

C. Storages

Storages cannot compete in the above described cost-optimized energy system configurations, except in full RES supply scenarios (see Figure 6). Cheap balancing power is supplied by the depreciated diesel gensets. This lowers the competitiveness of battery storages. If geothermal power is available and considered in the investigated energy system, it dominates the energy supply as base load power plant. The existing diesel gensets are the economically most attractive peak demand power supply option.

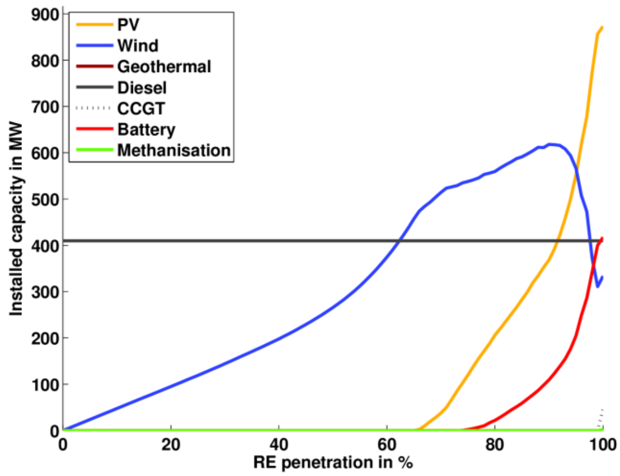

Figure 6 Electrical output power of power plants and storages plotted against the renewable electricity share. Battery storages emerge at RES shares greater than 75 %. Renewable power methane as mid to long term storage plays almost no role except from the last few percentages of renewable electricity generation.

IV. Conclusions

RES are competitive to the current energy supply systems on the eastern Caribbean islands, which are mostly based on diesel gensets. Disregarding geothermal power, wind power balanced by already depreciated diesel gensets is the preferred renewable energy source, due to high full load hours and low seasonal variability of wind power. Substituting diesel based energy supply by investing in wind power plants is on mid-term economically feasible. The most promising system configuration considering an interconnection of the islands is large scale geothermal energy supply including one transmission line from an island with geothermal energy potential to Barbados (no access to geothermal energy). Economics of transmission systems are highly dependent on utilization, therefore a constant energy source combined with a demand profile with low seasonal variability is the ideal combination. By introducing large scale geothermal power combined with a HVDC power line from St. Lucia to Barbados can significantly decrease the LCOE of all four islands at very high RES penetration.

By making decision to invest in new renewable power capacities it should be considered whether energy supply in the end will rely on local generation on each islands or based on large utilization of geothermal power with transmission to Barbados. Both supply strategies are feasible but following different paths to the final system.

For implementing the most favorable energy supply strategy, mainly based on geothermal power, a detailed exploration of the assumed geothermal potential has to be performed. Moreover the electricity utilities of St. Lucia and Barbados have to agree on building a transmission line between both islands.

V. Assumptions

The above described model has some limitations in order to simplify the optimization problem. The distribution system on each island is assumed as to be sufficient to distribute power from all power plants to the consumers. In other

words: A copper plate model is used to describe the grid on each island. The simulations in this work are performed with data in an hourly resolution. Effects which occur in sub-hour time scale are neglected. Power plants have no discrete size. They are treated as one power plant with aggregated output power per power plant type and island.
The future development of the electricity demand on the investigated islands is hardly predictable. For this reason the calculations have been performed with the electricity demand from the year 2010. Cost for imported fuel is likewise hard to predict but it's crucial for the competitiveness of renewable energies. Hence, the cost for imported Diesel is assumed with 1 USD/l. The existing diesel gensets vary significantly in year of commissioning and capacity which has influence on the efficiency. In order to simplify, the efficiency of all current diesel gensets is assumed with 30 %. The applied weighted average cost of capital (WACC) is set to 0.07. Table 1 depicts assumed financial and physical parameters of considered power plants and other system components for the year 2012.

Table 1. Key assumptions of financial parameters for investments in the year 2012 (Table 1 continued)

Financial parameters	Capex	Fixed Opex	Var. Opex	Lifetime
Photovoltaics	2,220 USD/kW	44 USD/kW	0	25 a
Wind energy	1,410 USD/kW	28 USD/kW	0	20 a
Geothermal	4,550 USD/kW	91 USD/kW	0	30 a
Diesel genset	0 USD/kW	35 USD/kW	0	20 a
Methanation	4,470 USD/kW	92 USD/kW	0	25 a
Electrolysis	2,820 USD/kW	56 USD/kW	0.17	20 a
Battery	290 USD/kW	6 USD/kW	0	10 a
Gas storage	1 USD/kW	0 USD/kW	0	50 a
Gas turbine	0 USD/kW	35 USD/kW	0	25 a
HVDC trans-mission line	11,070 USD/MW/km	111 USD/MW/km/a	0	50 a

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