GOVERNMENT OF JAMAICA
MINISTRY OF SCIENCE, TECHNOLOGY, ENERGY AND MINING

Grid Impact Analysis and Assessment for Increased Penetration of Renewable Energy into the Jamaican Electricity Grid

Final report

November 2013

CONTENTS

I. INTRODUCTION

The Ministry of Science, Technology, Energy and Mining (MSTEM) of Jamaica has set an objective to its electricity sector: generating 30% of the country's electricity from renewable sources by 2030. Building this kind of policy requires involvement and cooperation of all major players in the sector, along to a relevant and coherent corpus of studies.

The present study is the first one undertaken by the MSTEM to consider introduction of large amount of renewable energy into the electricity network. Its aim is to assess impacts of these renewables, on both investments to be made on the electricity network to maintain safe operation and Levelized costs of electricity to which producers are likely to be confronted to. For this study, the MSTEM has appointed as consulting team a consortium formed by Electricité de France (EDF) and its partner Hinicio.

The present report is the final report of this study, issued at the end of November, 2013.

It presents all methodological elements used by the consultant to conduct this study and all relevant results obtained by this methodology. It is a partial recapitulation of interim reports n° 1, 2, 3 and 4, and contains new elements concerning the Levelized costs of electricity. Finally it brings a conclusion to this study, in which the consultant gives recommendations, based on this work and its own experience, for the Jamaica electricity network to accommodate Variable Renewable Energy (VRE) sources by 2030.

Section 2 of this report contains all methodological elements and relevant results concerning the validation of the Jamaica electricity network steady-state model, the construction of a probabilistic model of this network and an assessment of its ability to accommodate VRE on the very short term.

Section 3 contains a recapitulation of Jamaica's potentials for renewable energies and a suggestion of various renewable asset portfolios allowing Jamaica to reach its objective for renewable electricity in 2030. Among these suggested portfolios, the MSTEM has chosen one target to be implemented by the consultant in its model.

Section 4 contains all methodological elements and relevant results concerning the construction of a probabilistic model of the Jamaica electricity network for 2030, including full conventional generation scenario and renewable generation scenario, and an assessment of its ability to accommodate VRE on the long term.

Section 5 contains all methodological elements and relevant results concerning the voltage management in presence of VRE, some regulatory aspects and the required reinforcements to maintain similar performance of the network in both scenarios and their cost estimates.

Section 6 of the present report is an introduction to dynamic impacts of VRE on the overall electrical system, including the generating units and the network itself.

Section 7 contains all methodological elements and relevant results concerning the total cost estimates of the selected renewable portfolio and the levelized costs of energy in both conventional and renewable scenarios.

Section 8 summarizes the major points of this study and makes recommendations for further actions to be undertaken by the MSTEM and all relevant players of the Jamaica electrical sector.

Finally section 9 and section 10 contain appendixes.

II. THE JAMAICA ELECTRICITY NETWORK IN 2013

II.1. 2013 GRID MODEL VALIDATION

II.1.1. Methodology

The aim of the grid model validation is to determine how consistent this model and all characteristics of the equipments it figures are. Given that both power flows through transmission lines and bus voltages strongly depend on electrical characteristics of the transmission lines and the transformers, this step is of high importance.

In order to assess the consistency of these models, the consultant runs load-flows with PSS-E at a particular operating point and compares results to real-time data provided by JPS through a snapshot of the Jamaica electricity grid. All discrepancies between load-flow results and snapshot are analysed and the model is adjusted accordingly.

The snapshot provided to the consultant by JPS figures estimated and measured voltages at all 138kV and 69kV buses and at some generating buses; all estimated and measured active and reactive loads; estimated and measured active and reactive power outputs of all generating units; and estimated and measured active and reactive power flows through all transmission lines, generating unit step-up transformers and 138/69kV transformers. This snapshot was recorded on the 26th of April, 2013 between 9:04 - 9:15AM (GMT-5).

First version of the snapshot exhibited a large mismatch between generation and consumption of active power. Loads have consequently been modified and new data provided to the consultant, directly through the PSS-E.

II.1.2. Snapshot description

II.1.2.a Generation

Table II-1 shows the active and reactive power outputs of generating units provided in the snapshot.

The total active power is 508MW. The total reactive power is between 153,82MVAR (estimated values) and 158,42MVAR (measured values). The consultant wishes to highlight that bus names are not strictly identical to the ones used in the model. This usual situation leads the consultant to interpret the data and make the following assumptions:

- BOG CC12 is represented in the model through bus 83 “CC GEN B”; this bus is connected to two generating units (“BSTMB” and “GT13B”) which produce, in addition with “GT12B” the approximately 90 MW and between 6 to 15 MVAr figured in the table below;
- HBB B6 is represented in the model through bus 57 “B6_BUS13”; this bus is connected to one generating unit which produces the approximately 47.5 MW and 19 MVAr figured in the table below;
- Wartsila Jep is represented in the model through buses 20, 21 and 104, respectively “JEP2” “JEP1” and “NEW JEP”; each of these busses is connected to several generating units which produce in total the approximately 99.5 MW and 35 MVAr figured in the table below;
- WKPP is represented in the model through buses 300 and 301 “JEPWK1” and “JEPWK2”; each of these buses are connected to three generating units which produce the approximately 51.5 MW and 18 MVAr figured in the table below.

Name	Estimated MW [1]	Measured MW	Estimated MVAR	Measured MVAR
BOG CC1	0,00	0,00	0,00	5,97
BOG CC12	90,12	90,45	6,36	0,00
BOG CC2	0,00	0,00	0,00	0,00
BOG GT11	0,00	-0,01	0,00	0,00
BOG GT12	0,00	0,00	0,00	3,71
BOG GT13	0,00	0,00	0,00	5,24
BOG GT3	0,00	0,00	0,00	-0,14
BOG GT6	0,00	0,00	0,00	0,00
BOG GT7	0,00	0,00	0,00	-0,14
BOG GT8	0,00	0,00	0,00	0,00
BOG GT9	0,00	0,00	0,00	0,00
BROILERS	1,53	1,66	0,12	0,00
HBB B6	47,50	47,54	19,48	19,25
HBB GT10	0,00	-0,09	0,00	-0,11
HBB GT4	0,00	0,00	0,00	0,04
HBB GT5	0,00	0,00	0,00	0,00
JAMALCO	-1,43	-1,42	0,68	0,00
JPPC	35,41	35,42	6,91	4,55
LWR HYDRO	3,69	3,70	1,02	1,00
MAGGOTTY HYDRO	0,00	0,00	0,00	0,00
OHARBOUR OH1	0,00	0,00	0,00	0,00
OHARBOUR OH2	51,28	50,02	16,39	16,86
OHARBOUR OH3	40,88	40,94	8,82	9,10
OHARBOUR OH4	51,97	52,28	24,59	25,16
RIO HYDRO A	1,93	2,02	0,46	0,00
RIO HYDRO B	0,91	1,00	0,46	0,00
ROARIVER HYDRO	3,60	3,60	1,00	1,00
ROCKFORT RF1	20,15	20,16	5,57	5,53
ROCKFORT RF2	5,21	5,19	6,95	7,00
UPRWHITE HYDRO	2,51	2,60	1,19	1,20
WARTSILA JEP	99,51	99,60	35,55	35,20
WIGTON	2,45	2,45	0,28	0,00
MUNRO	0,00	0,08	0,00	-0,01
WKPP	51,55	51,60	18,00	18,00
Total	508,79	508,79	153,82	158,42

Table II-1 : Snapshot generation plant

II.1.2.b Loads

Table II-2 shows the load values provided in the snapshot. These values are different from the values provided by the metering. In fact, some loads are not metered on the Jamaica electricity grid and JPS had to estimate their values.

[1] Estimated values are thought to be direct outputs of JPS dispatching center real-time state-estimator

Bus Name	Pload (MW)	Qload (Mvar)
TREDEGAR 69,000	15,30	4,68
HOPE 69,000	17,28	13,62
MILCHELT 69,000	10,73	4,61
PARADISE 69,000	13,82	0,78
BLEDGE 69,000	0,69	0,26
CANE RIV 69,000	6,46	3,48
TOLLGATE 69,000	0,00	0,00
HIGHGATE 69,000	2,16	0,13
QUEENS D 69,000	19,25	12,91
OCHO 69,000	10,64	4,61
BOGUE_69 69,000	28,80	3,39
STEEL MI 69,000	0,00	0,00
ROSE HAL 69,000	8,08	1,97
OH1 13,800	4,10	0,65
RF1 13,800	0,00	0,00
CEMENT C 69,000	13,03	8,29
OBAY69 69,000	12,44	6,40
DUNCANS6 69,000	3,65	0,49
OH2 13,800	0,00	0,00
RF2 13,800	0,00	0,00
3MLS69 69,000	14,26	6,92
WBLVD69 69,000	38,09	7,71
OH3 13,800	0,00	0,00
PORT ANT 69,000	4,13	3,31
OH4 13,800	0,00	0,00
WIPP 69,000	0,00	0,00
B6_BUS13 13,800	0,00	0,00
GREENWOO 69,000	5,63	1,54
LYSSONS 69,000	4,50	0,01
PORUS 69,000	0,00	0,00
R RIVER 69,000	8,62	3,38
MARTHA B 69,000	2,22	0,85
WKH69 69,000	17,36	4,82
PNASUS69 69,000	5,08	0,00
ANNOTTO 69,000	3,70	0,80
MANDEVI 69,000	0,00	0,00
UW RIVER 69,000	0,89	0,27
KNDAL 69 69,000	11,66	2,40
MONYMUSK 69,000	4,20	1,95
OROCABES 69,000	3,30	1,35
MAGGOTTY 69,000	8,65	1,43
D&G 69,000	0,00	0,00
UP PARK 69,000	22,09	8,69
TWICKENH 69,000	12,69	2,54
MAY PEN 69,000	9,18	3,17
PAJ 69,000	14,33	4,71
GROAD_69 69,000	14,02	4,38
CSPRING 69,000	10,24	2,78
S_TREE6 69,000	16,03	2,11
NAGGOS H 69,000	13,31	8,39
GOODYEAR 69,000	4,39	0,94
HBAY_69 69,000	37,44	12,47
RFORT69 69,000	10,91	3,44
RHODEN P 69,000	10,87	4,64
DUHANEY6 69,000	14,44	4,86
CARDIFF 69,000	10,30	3,93
JAB13.8 13,800	0,00	0,00
JAM13.8 13,800	1,42	0,00
Total	*500,37*	*170,04*

Table II-2: Snapshot Loads

II.1.2.c Bus voltages

Table II-3 and Table II-4 show voltages on both 138kV and 69kV network provided in the snapshot.

Name	Estimated Voltage (KV)	Measured Voltage (KV)
BEL 138KV BUS	136,03	136,39
BOG 138KV BUS	135,71	136,72
DUH 138KV BUS A	136,91	136,49
DUN 138KV BUS A	136,53	138,06
JEP 138KV GEN B	141,45	141,00
KEN 138KV BUS A	138,35	138,57
OHB 138KV NBUS	140,84	139,18
PAR 138KV BUS N	139,87	138,59
SPU 138KV NBUS	138,91	136,73
TRE 138KV BUS A	137,73	140,77

Table II-3: Bus voltages on the 138kV network

Name	Estimated Voltage (KV)	Measured Voltage (KV)
ANN 69KV BUS	70,18	70,56
BEL 69KV NBUS	70,64	70,58
BLK 69KV BUS	70,12	70,01
CMT 69KV BUS	70,33	69,70
BOG 69KV NBUS	71,12	114,61
BOG GT3 69KV B	71,14	0,21
CRV 69KV BUS	69,87	69,43
BOG GT9 69KV C	71,13	0,21
CAR 69KV BUS A	69,86	69,54
CON 69KV BUS A	69,77	70,25
D&G 69KV BUS A	70,60	0,00
DUH 69KV BUS C	70,61	70,99
DUN T1 69KV BUS	70,59	69,32
GYR 69KV BUS A	68,52	0,00
GWD 69KV BUS A	70,07	69,43
GRD 69KV BUS A	70,47	70,28
HAL 69KV BUS A	70,55	0,00
HGT 69KV BUS A	70,18	69,89
HOP 69KV BUS A	69,53	70,44
HBB 69KV NBUS N	70,74	70,15
JBR 69KV BUS A	70,03	70,31
JPC 69KV BUS A	70,47	67,17
KEN T1 69KV BUS	70,69	73,22
ALK 69KV BUS A	70,61	69,00
LWR 69KV BUS A	70,30	70,05
LYS 69KV BUS A	68,43	0,00
MAG 69KV BUS A	68,25	70,36
BOG ST 14 69KV	71,19	70,64
MAR 69KV BUS A	70,31	0,00
MAY 69KV BUS A	70,16	0,00
MIC 69KV BUS A	69,73	0,00
MON 69KV BUS A	69,92	71,24

NAG T1 69KV BUS	69,75	0,00
OCH 69KV BUS A	70,02	69,90
OHB 69KV BUS M	69,40	22,42
ORA 69KV BUS A	70,42	0,00
OBY 69KV BUS A	69,80	70,52
PAJ 69KV BUS A	70,78	72,00
SPU T1 69KV A	69,61	71,67
PDS 69KV BUS A	70,25	69,81
PAR 69KV BUS B	70,52	71,77
ST_JAGO 69KV	70,37	0,00
PTO 69KV BUS A	69,99	69,03
POR 69KV BUS A	69,51	3,62
QDR 69KV BUS A	70,65	70,08
RHO 69KV BUS A	68,96	70,25
RIO 69KV BUS A	70,54	0,00
RVR 69KV BUS A	69,85	69,36
RFT T1 69KV BUS	70,44	70,91
ROS 69KV BUS A	70,24	69,71
SPV 69KV BUS A	70,00	68,67
SPU T1 69KV BUS	69,60	71,67
WIG 69KV BUS A	69,62	71,02
SUN 69KV BUS A	69,79	0,00
3ML 69KV BUS A	70,26	70,82
TOL 69KV BUS A	70,32	0,00
TRE T1 69KV BUS	70,06	69,96
TWK 69KV BUS A	70,16	70,05
UPC 69KV BUS A	69,83	69,75
UWR 69KV BUS A	70,37	0,00
WBL 69KV BUS A	69,98	69,78
WKH 69KV BUS A	69,73	69,31
WHM 69KV BUS A	69,13	0,00
WKPP 69 KV BUS	70,90	70,67

Table II-4: Bus voltages on the 69kV network

From these tables, it must be noted that significant differences appear between estimated and measured values and that some measured values are missing or inconsistent. Consequently, model results will be considered valid if voltages at bus bars are within a range equal to the delta between estimated and measured value at the considered bus bar, from any of the estimated or measured value, as the consultant has no means to know which of the two values is the most reliable.

II.1.3. Simulation results

II.1.3.a Generation output

Name	Simulated MW	Measured MW	Delta	Simulated MVAR	Measured MVAR	Delta
BOG CC1	0,00	0,00	0	6,75	5,97	0,78
BOG CC12	90,45	90,45	0	0,00	0,00	0
BOG CC2	0,00	0,00	0	0,00	0,00	0
BOG GT11	0,00	-0,01	0,01	0,00	0,00	0
BOG GT12	0,00	0,00	0	7,05	3,71	3,34
BOG GT13	0,00	0,00	0	6,70	5,24	1,46
BOG GT3	0,00	0,00	0	0,00	-0,14	0,14
BOG GT6	0,00	0,00	0	0,00	0,00	0
BOG GT7	0,00	0,00	0	0,00	-0,14	0,14
BOG GT8	0,00	0,00	0	0,00	0,00	0
BOG GT9	0,00	0,00	0	0,00	0,00	0
BROILERS	1,66	1,66	0	0,12	0,00	0,12
HBB B6	47,54	47,54	0	19,61	19,25	0,36
HBB GT10	0,00	-0,09	0,09	0,00	-0,11	0,11
HBB GT4	0,00	0,00	0	0,00	0,04	-0,04
HBB GT5	0,00	0,00	0	0,00	0,00	0
JAMALCO	-1,42	-1,42	0	0,00	0,00	0
JPPC	35,42	35,42	0	9,06	4,55	4,51
LWR HYDRO	3,70	3,70	0	1,00	1,00	0
MAGGOTTY HYDRO	0,00	0,00	0	0,00	0,00	0
OHARBOUR OH1	0,00	0,00	0	0,00	0,00	0
OHARBOUR OH2	50,02	50,02	0	17,64	16,86	0,78
OHARBOUR OH3	40,94	40,94	0	9,71	9,10	0,61
OHARBOUR OH4	50,17	52,28	-2,11	25,65	25,16	0,49
RIO HYDRO A	3,02	2,02	0	0,92	0,00	
RIO HYDRO B		1,00			0,00	
ROARIVER HYDRO	3,60	3,60	0	1,00	1,00	0
ROCKFORT RF1	20,16	20,16	0	7,98	5,53	2,45
ROCKFORT RF2	5,19	5,19	0	7,97	7,00	0,97
UPRWHITE HYDRO	2,60	2,60	0	1,20	1,20	0
WARTSILA JEP	99,6	99,60	0	39,33	35,20	4,13
WIGTON	2,45	2,45	0	0,00	0,00	0
MUNRO	0,00	0,08	-0,08	0,00	-0,01	0,01
WKPP	51,60	51,60	0	17,84	18,00	-0,16
Total	***506,70***	***508,79***	***-2,09***	***179,53***	***158,42***	***21,12***

Table II-5: Comparison between expected and simulated generation outputs

From the table above, it can be noted that total delta in active power is not significant. Total delta in reactive power is much higher and cannot be disregarded. This issue is addressed later in the document, conjointly with the voltage.

II.1.3.b Bus Voltages

Name	Estimated Voltage (kV)	Measured Voltage (kV)	Admissible Delta	Simulated Voltage (kV)	Variation
BEL 138KV BUS	136,03	136,39	0,3%	135,82	0,2%
BOG 138KV BUS	135,71	136,72	0,7%	136,07	0,3%
DUH 138KV BUS A	136,91	136,49	-0,3%	136,55	0,0%
DUN 138KV BUS A	136,53	138,06	1,1%	136,82	0,2%
JEP 138KV GEN B	141,45	141	-0,3%	141,51	0,0%
KEN 138KV BUS A	138,35	138,57	0,2%	138,96	0,3%
OHB 138KV NBUS	140,84	139,18	-1,2%	140,73	0,1%
PAR 138KV BUS N	139,87	138,59	-0,9%	140,26	0,3%
SPU 138KV NBUS	138,91	136,73	-1,6%	139,17	0,2%
TRE 138KV BUS A	137,73	140,77	2,2%	137,52	0,2%

Table II-6: Comparison between expected and simulated 138 kV bus voltages

All 138kV network bus voltages are within acceptable range, which is considered a good indicator of the reliability of the model.

Name	Estimated Voltage (kV)	Measured Voltage (kV)	Admissible Variation	Simulated Voltage (kV)	Variation
ANN 69KV BUS	**70,18**	**70,56**	**0,5%**	**69,54**	**0,9%**
BEL 69KV NBUS	**70,64**	**70,58**	**-0,1%**	**70,41**	**0,2%**
BLK 69KV BUS	70,12	70,01	-0,2%	69,96	0,1%
CMT 69KV BUS	70,33	69,7	-0,9%	70,26	0,1%
BOG 69KV NBUS	71,12	114,61	37,9%	71,1	0,0%
BOG GT3 69KV B	71,14	0,21	-33776,2%		
CRV 69KV BUS	69,87	69,43	-0,6%	69,83	0,1%
BOG GT9 69KV C	71,13	0,21	-33771,4%		
CAR 69KV BUS A	**69,86**	**69,54**	**-0,5%**	**69,01**	**0,8%**
CON 69KV BUS A	69,77	70,25	0,7%	70,52	0,4%
D&G 69KV BUS A	70,6	0	99900,0%	70,73	0,2%
DUH 69KV BUS C	70,61	70,99	0,5%	70,75	0,2%
DUN T1 69KV BUS	70,59	69,32	-1,8%	69,75	0,6%
GYR 69KV BUS A	68,52	0	99900,0%	68,79	0,4%
GWD 69KV BUS A	70,07	69,43	-0,9%	69,83	0,3%
GRD 69KV BUS A	70,47	70,28	-0,3%	70,48	0,0%
HAL 69KV BUS A	70,55	0	99900,0%	71,17	0,9%
HGT 69KV BUS A	70,18	69,89	-0,4%	69,7	0,3%
HOP 69KV BUS A	69,53	70,44	1,3%	69,44	0,1%
HBB 69KV NBUS N	70,74	70,15	-0,8%	70,72	0,0%
JBR 69KV BUS A	**70,03**	**70,31**	**0,4%**	**70,7**	**0,6%**
JPC 69KV BUS A	70,47	67,17	-4,9%		
KEN T1 69KV BUS	70,69	73,22	3,5%	70,94	0,4%
ALK 69KV BUS A	70,61	69	-2,3%		
LWR 69KV BUS A	**70,3**	**70,05**	**-0,4%**	**69,5**	**0,8%**
LYS 69KV BUS A	68,43	0	99900,0%	68,73	0,4%

MAG 69KV BUS A	68,25	70,36	3,0%	69,98	0,5%
BOG ST 14 69KV	71,19	70,64	-0,8%	71,13	0,1%
MAR 69KV BUS A	70,31	0	99900,0%	69,73	0,8%
MAY 69KV BUS A	70,16	0	99900,0%	70,91	1,1%
MIC 69KV BUS A	69,73	0	99900,0%	69,69	0,1%
MON 69KV BUS A	69,92	71,24	1,9%	70,83	0,6%
NAG T1 69KV BUS	69,75	0	99900,0%	69,9	0,2%
OCH 69KV BUS A	**70,02**	**69,9**	**-0,2%**	**69,13**	**1,1%**
OHB 69KV BUS M	69,4	22,42	-209,5%	70,84	2,1%
ORA 69KV BUS A	70,42	0	99900,0%	69,87	0,8%
OBY 69KV BUS A	69,8	70,52	1,0%	69,72	0,1%
PAJ 69KV BUS A	70,78	72	1,7%	70,61	0,2%
SPU T1 69KV A	69,61	71,67	2,9%	70,86	1,1%
PDS 69KV BUS A	70,25	69,81	-0,6%	70	0,3%
PAR 69KV BUS B	70,52	71,77	1,7%	71,18	0,8%
ST_JAGO 69KV	70,37	0	99900,0%		
PTO 69KV BUS A	69,99	69,03	-1,4%	68,89	0,2%
POR 69KV BUS A	69,51	3,62	-1820,2%	70,94	2,1%
QDR 69KV BUS A	70,65	70,08	-0,8%	70,67	0,0%
RHO 69KV BUS A	68,96	70,25	1,8%	70,51	0,4%
RIO 69KV BUS A	70,54	0	99900,0%	69,5	1,5%
RVR 69KV BUS A	69,85	69,36	-0,7%	68,93	0,6%
RFT T1 69KV BUS	70,44	70,91	0,7%	70,45	0,0%
ROS 69KV BUS A	70,24	69,71	-0,8%	70,16	0,1%
SPV 69KV BUS A	70	68,67	-1,9%		
SPU T1 69KV BUS	69,6	71,67	2,9%	70,86	1,1%
WIG 69KV BUS A	69,62	71,02	2,0%	70,93	0,1%
SUN 69KV BUS A	69,79	0	99900,0%	69,72	0,1%
3ML 69KV BUS A	70,26	70,82	0,8%	70,14	0,2%
TOL 69KV BUS A	70,32	0	99900,0%	71,12	1,1%
TRE T1 69KV BUS	**70,06**	**69,96**	**-0,1%**	**70,23**	**0,2%**
TWK 69KV BUS A	**70,16**	**70,05**	**-0,2%**	**70,3**	**0,2%**
UPC 69KV BUS A	**69,83**	**69,75**	**-0,1%**	**70,11**	**0,4%**
UWR 69KV BUS A	70,37	0	99900,0%	69,7	1,0%
WBL 69KV BUS A	69,98	69,78	-0,3%	69,96	0,0%
WKH 69KV BUS A	69,73	69,31	-0,6%	69,83	0,1%
WHM 69KV BUS A	69,13	0	99900,0%	70,7	2,3%
WKPP 69 KV BUS	**70,9**	**70,67**	**-0,3%**	**71,31**	**0,6%**
Average	***70,11***	***71,20***	***1,55%***	***70,19***	***0,12%***

Table II-7: Comparison between expected and simulated 69 kV bus voltages

Results for 69 kV network bus voltages are very close to the expected values. Nevertheless, 10 buses are outside of acceptable range, with the biggest delta being bus Ocho Rios 69kV. At this bus, voltage in per unit is 1.002 instead of 1.015. Such a delta has no impact on further results and the consultant recommends ignoring it.

From Table II-5, Table II-6 and Table II-7, the model is considered reliable and precise enough to go on with the study, given that:

- all measurements and state estimations are subject to uncertainties;
- the snapshot provided to the consultant was obtained over a period of 11 minutes. Conditions of load, generation and voltages may have changed over the period, leading to a dispersion in the measurements impossible to reproduce with the model;
- updated load values provided by a PSS-E file are subject to uncertainties; sum of transmission line transits at several buses show different values for the load; range of variation is small, but large enough for the simulation results to be included in the acceptable range of variation;
- data are missing for several buses, including generating unit bus bars;
- real operation data are missing for shunt capacitors and tap ratio of transformer; all data concerning these two items were provided through PSS-E file, with no regard to any other sources.

These issues are commonly met during such activity, and should not be considered problematic. Some data are inconsistent, leading the consultant to make significant changes in the model; these changes were made according to his calculation and experience and are subject to uncertainties. These changes are detailed in the next chapter.

II.1.3.c Major changes in model

The main issue faced by the consultant when adjusting the model to the snapshot behaviour was the voltage profile across the whole grid, and its consequences on reactive power flows.

First technique one can use is to set all generating units in fixed (P, Q) mode. If all tap positions are correctly adjusted and shunt capacitors correctly engaged, voltage profile should be close to its target and variation of the slack bus outputs to zero. In the case of the Jamaican electricity grid, the model showed large variation of the slack bus reactive power output and a very low voltage profile across the network.

When checking lines characteristics, it appeared to the consultant that line susceptance for all 138kV is unusually low. Susceptance depends mainly on size and types of conductors and on voltage level. This parameter is likely to increase with the size and the voltage level. The consultant has verified this assumption all along its experience. In the case of the Jamaican electricity grid, all 138kV lines show smaller susceptances than all 69kV lines. According to the use of similar conductors on both 138kV and 69kV network, the consultant has made the hypothesis that all susceptances of 138kV lines are 10 times too small and has adjusted them. These changes fit reactive power flows on the lines: the snapshot exhibits generation of reactive power by most of the lines, which was expected given the level of the load at the time of recording and the resulting charging of the lines. No other change in the network could help bring the simulation results as close to the snapshot as the adjustment of susceptances did.

When checking voltage profiles at generating unit bus bars, it appeared to the consultant that, if voltages on medium voltage side of generating unit step-up transformers in Rockfort were maintained close to the values provided in the snapshot and tap changes of these transformers remained in their predefined positions, voltage in Rockfort was extremely high, potentially above permissible limits, whereas generating units were set on their maximum reactive power outputs. Scheduled voltages on the medium voltage side of the transformers were sometimes not even achievable, the generating units reaching their limits below these values. This statement of facts led the consultant to revise tap positions of the transformers for these generating units, changing from 1.05/1 per unit ratio to 1.025/1. In the same idea, recorded voltage at West Kingston Power Plant in the snapshot with relatively low reactive power outputs from units connected at the bus and predefined tap positions were not achievable. After revising tap positions, also changing from 1.05/1 per unit ratio to 1.025/1, the results were significantly improved. Generally speaking, the choice made by the PSS-E network model maker for modelling the transformers in the Jamaica electricity grid presents important risks. The option chosen in PSS-E lies on bus bar nominal voltage and per unit calculations, instead of real tap settings and apparent power of transformers. It has led into ambiguous situations at least in Bogue, where some step-up transformers are clearly not well modelled and tap positions not harmonized, West Kingston Power Plant tap ratio of step-up transformers do not fit real capability of the transformers.

All changes made by the consultant are listed in appendix.

Variation between simulation results with and without changes made by the consultant is significant, the simulations with changes bringing final results very close to the snapshot. Consequently these changes seem appropriate. However, the consultant has no means to verify those assumptions, which should be investigated by the TSO. Without any further information, the consultant will go on with the study using this adjusted model.

II.2. PROBABILISTIC MODEL DESCRIPTION

II.2.1. Probabilistic approach

Aim of this chapter is to determine how much renewables the Jamaica electricity grid can accommodate without any reinforcement and without deteriorating its steady-state operational safety performance. In order to do so, the consultant has suggested using a probabilistic approach. This kind of methodology has been developed for about 20 years, but was first restricted to the study of a unique voltage level network, with as few buses as possible and with simplified simulation code. Developments in IT technologies, hardware and software, now allow us to use this approach with any type of network, regular load-flow simulation software, such as PSS-E, and simple 2-core processor laptop.

The main point of the probabilistic approach is to run a large number of simulations in order to create a more holistic view of the steady-state behaviour of a grid. With this deeper understanding of the grid, planning engineers are able to answer quickly and efficiently two questions:

- What is the most critical situation for the grid?
- How often can this situation appear?

Being able to respond to these questions leads to change paradigm of network planning, from sizing equipments based on a so-called worst case scenario, to sizing investments based on a risk study. Many fields of science and engineering have followed the same path from deterministic sizing to probability-based decision making, where the risk is measured not only in magnitude but also in occurrence. The more complex a system is the more difficult it is to select the “worst case” scenario and the less efficient deterministic network planning is: performance of the grid may not reach expected criteria and investments may largely increase. In the case of an electricity grid, integration of VRE makes these calculations even more complicated and probabilistic approach necessary. The methodology used to compute maximum VRE penetration rate is described in the following section.

This general concept being presented, going into probabilistic approach of a study requires being able to gather sufficient information: this means precise and reliable information, in sufficiently large quantity. In the case of this study, most of the data was gathered during the first assignment of the consultant in Jamaica. All these data have been described in the previous *"Inception report"*. In the present section, the use of these data is described and their limitations explained.

The probabilistic approach also requires a specific tool. The tool used by JPS is PSS-E and so the consultant has chosen to work with a compatible tool. The general functioning of the tool is described in this section.

II.2.2. Methodology

II.2.2.a Steady-state operational safety criteria

The main point of the methodology is to implement VRE sources in the Jamaica electricity grid and assess their impact on power flows through the transmission lines. To do so, the consultant needs to establish a performance standard to which further situation with VRE can be compared on a clear and well defined basis.

One relevant criterion to measure the performance of the Jamaica electricity grid is the steady-state operational safety. This criterion is defined as the probability for any line in the network to be overloaded during the year. This probability is calculated in situation N and N-1, with one line out of service. Calculated for the Jamaica electricity grid in 2013, without any additional generating unit, this criterion gives a clear picture of the steady-state performance of the grid.

The same criterion is then calculated with additional renewable sources and compared with the reference. The maximum steady-state penetration rate is defined as the maximum of energy renewable sources can provide to the grid without deteriorating its performance.

Calculation of the criterion is directly based on probabilistic simulations: a large number of possible states of the grid over a period of one year are simulated and the probability for any line to be overloaded is defined as the ratio between simulations with one or more lines overloaded and the total number of simulations.

These simulations, and the tools used, are described later in the document.

II.2.2.b Renewable portfolio

The penetration rate of renewables in the Jamaica electricity grid is expected to reach 30% of electricity generated in 2030. Among them, a large amount of solar and wind power is planned to be in operation at this date. Solar and wind power are variable, cannot be dispatched and have very limited capabilities of controlling frequency and voltage. For these reasons, they are considered the most difficult electricity sources to accommodate.

Reaching this objective requires for the Jamaica electricity system to follow a trajectory and start integrating more and more renewable from now on. A call for tenders has already been launched but there was no study carried out on potential impacts of renewables on the Jamaica electricity grid so far.

One of the tasks assigned to the consultant is to determine the maximum penetration rate of renewables achievable in 2013 by the Jamaica electricity grid without any reinforcement, from the steady-state point of view. To do so, the consultant has built a renewable portfolio for 2013. Hydro power projects are not likely to be in operation on short term horizon. Waste and biomass based projects suffer the same issue. Only solar and wind power projects are considered to be possibly commissioned on short term, waste, biomass and hydro projects coming in operation on medium or long term horizons. The consultant has thus built the following portfolio[2]:

Technology	Site name	Capacity (MW)	Capacity factor	Annual energy (GWh)
Hydro run-of-river	Rio Bueno	2,5	0,6	13,1
Hydro run-of-river	Maggoty Falls	6,3	0,6	33,1
Hydro run-of-river	Upper White River	3,8	0,6	20
Hydro run-of-river	Lower White River	4	0,6	21
Hydro run-of-river	Roaring River	3,8	0,6	20
Hydro run-of-river	Constant Spring	0,8	0,6	4,2
Hydro run-of-river	Ram's Horn	0,6	0,6	3,2
PV	Paradise 1	49,5	0,22	93,1
PV	Paradise 2	30	0,22	56,5
PV	Old Harbour	30	0,21	55,7
PV	Kelly's Pen A	20	0,22	38,4
PV	Micham	25	0,21	46,2
PV	Parnassus	43	0,21	80,2
Wind	Wigton 1	20,7	0,30	54,4
Wind	Wigton 2	18	0,38	59,1
Wind	Munro	3	0,29	7,5
	Total	261		605,8

Table II-8: Renewable portfolio in 2013

For new generating units, connection points in the model are as follow:

Technology	Site name	Connection point
PV	Paradise 1	Paradise – Orange Bay 69 kV Line
PV	Paradise 2	Paradise – Maggoty 69 kV Line
PV	Old Harbour	Old Harbour – Tredegar 138 kV Line
PV	Kelly's Pen A	Old Harbour 69 kV Substation
PV	Micham	Maggoty – Spur Tree 69 kV Line
PV	Parnassus	Parnassus Substation (Old)

Table II-9: Connection points of new renewable units

The steady-state operational safety criterion is calculated once this portfolio implemented in the model. If necessary, maximum power installed at each site is reduced until the criterion reaches the reference standard.

II.2.3. Probabilistic model

In this section is described the probabilistic model built by the consultant and which serves as input to its tool.

[2] The selected portfolio for 2013 is based on the portfolio n°3 presented in the chapter III. Construction of Renewable Energy Portfolios, out of which only solar and wind power are implemented, in addition to existing renewables. Decision to include the large potential wind power site Winchester is not yet finalized. The consultant has then decided to exclude it from its study for 2013. This issue is addressed later in the document.

II.2.3.a Load

In order to create a relevant view of the Jamaica electricity grid, the consultant has built a law of probability to represent variation of the load over the study period. This law allows the probabilistic tool described further in this document to run simulations on the whole range of variation of the load. Thus the consultant is able to identify any issue that may occur in peak and/or off-peak period.

The consultant was provided with 15 minute time step time series of the load over the year 2012. From those time series, laws of probability for the load have been created through an optimized truncated uniform law-based Kernel smoothing estimation. This method allows the consultant to reduce uncertainties that may occur with a simple histogram technique.

II.2.3.b Solar power

As solar power has priority in the merit order, is not controllable in active power and has very limited control capabilities of voltage, solar generating units are modelled as fixed power factor machines, with power factor equal to 1 and unknown power output.

In order to assess impact of solar power, the consultant has built a law of probability to represent generation of solar units in accordance with real irradiance conditions in Jamaica. From this law, the consultant is able to probabilistically generate power outputs for all solar units that serve as input to his tool.

Maximum power of each site is given in the portfolio, built from data gathered in Jamaica. For more information, refer to the following section 3.

Power generated by solar units is calculated by multiplying maximum power by a law of probability normalized between 0 and 1.

The law is created with the same Kernel smoothing estimation as described above for the load. Calculation is based on time series provided by the Ministry of Science, Technology, Energy and Mining of Jamaica. Transfer functions between irradiance and effective power generated was provided by the Seattle-based company 3 TIER through a study conducted for World Watch on September 2012 (see document [18]).

II.2.3.c Wind power

A similar approach as for solar power is used for wind power.

The law of probability for wind power was directly taken from a histogram built on Wigton wind measurements conducted in 2012 and provided by the Ministry of Science, Technology, Energy and Mining of Jamaica.

II.2.3.d Hydro power

Hydro power generating units are separated into two categories: run-of-river and dam.

First category has priority in merit order, is considered not controllable in active power, since any discount of power results in a waste of valuable resource, but has voltage control capabilities. Run-of-river are modelled as voltage controlled machines, with maximum tan (φ) of 0.4 and fixed seasonal power output.

Second category has not the same priority in merit order and is considered fully controllable in both active and reactive power. As water is a valuable and variable resource, usage of a dam varies seasonally and can be optimized weekly or even daily. Dams are consequently modelled as voltage controlled machines, with reactive generation capabilities and dispatching price. The consultant has decided to use a varying price on a seasonal scale in order to represent realistic usage of the resource. When resource is abundant, generation cost from dam is set at 0: dams will play major role in the electricity dispatch. When resource is rare, because of the capability of storage, dam is considered able to produce power, if needed. Thus optimization of usage depends on requirement of the electricity grid and not resource: the price of hydro power from a dam is set equal to peak-load machine generation cost. During intermediate season, price is set in the middle of the merit order.

No time series were available for hydro power. The consultant has decided to use a study conducted by Sino Hydro, in which two drainage basins of Jamaica are described. It led the consultant to create three seasons for hydro resource: high flow in November and December, low flow in July and August and intermediate flow the rest of the year. According to that study, ratio between high and low flows is 7 to 1 in the Yallah basin and 5.3 to 1 in the northern blue mountain basin. In the rest of the Jamaican territory, ratio is set at 6 to 1, without further information.

II.2.3.e Correlations

In the above described renewable portfolio, several solar and wind power sites are selected. The resource at those sites is not identical neither in intensity, which is translated through various maximum amount of MW generated, nor in duration, which is translated through the shape of the law of probability of the site. Several laws of probability might then be necessary to faithfully represent the whole portfolio.

In order to rule out this issue, the consultant has to investigate possible correlations between the sites. Generally speaking, correlation between 2 random variables is a measure of their joint evolution. If correlation between two sites is high, power output of the sites will behave in the same manner, reaching their maximum and minimum power at the same time, and meaning the geographical smoothing is very low. On the opposite, very low correlation factors mean high geographical smoothing, and mean greater support to the Jamaica electricity grid.

Correlations between solar sites proved to be very high, superior to 0.9, whereas correlations between wind sites were about 0.4. Thus the consultant has decided to model solar sources by only one law of probability and wind power through two laws: one for the Wigton region and one for Winchester. Should Winchester be replaced in 2013 and 2030 by another wind site, a new law would be built for this site and correlations calculated again.

Correlations might also exist between solar and/or wind power, and load or hydro power. These seasonal correlations can lead to create several laws of probability for a single site, depending on the period of study.

To properly calculate all correlations, the consultant needs to dispose of times series in MW for solar, wind, hydro power and load, over a common period of time, necessarily longer than the period of study. For this study, these data were not available. Solar, wind and hydro resources were mainly described through primary figures, irradiance, wind and flow respectively. Wind data were not available at appropriate height for most of the sites, and hydro was only described through seasonality of flow across two different drainage basins of Jamaica.

The consultant had to extrapolate 10 meter height measurement for wind into wind turbine output in MW. To do so, the consultant had to use first a power law with an alpha coefficient of 1/7, and then the Vestas 80m 2MW 104dB transfer function.

Correlations with hydro could not be calculated, as no time series were available. This issue is treated through seasonality. Laws of probability have been calculated for the three seasons identified by the consultant: high flow period, intermediate flow period and low flow period.

Calculation showed taking into account seasonality for solar, wind and load was not required because each of these variables had the same law on each hydro flow period.

The following correlations were calculated:

Day				
	Load	Wind Wigton	Wind Winchester[3]	Solar
Load	1	0,07	0,22	0,13
Wind Wigton	0,07	1	0,36	-0,01
Wind Winchester	0,22	0,36	1	0,10
Solar	0,13	-0,01	0,10	1
Night				
	Load	Wind Wigton	Wind Winchester	Solar
Load	1	0,07	0,22	0
Wind Wigton	0,07	1	0,21	0
Wind Winchester	0,22	0,21	1	0
Solar	0	0	0	1

Table II-10: correlations between all laws of probability of the probabilistic model

Separation was made between day and night as obvious variation in solar behaviour appears. These correlations were supposed constant over the whole year.

II.2.4. General Functioning of the tool

II.2.4.a PSS-E OPF

The network simulations are conducted through the worldwide well-know Siemens PTI tool, PSS-E. This tool is also in use at JPS.

The consultant uses an additional module to this tool, PSS-E Optimal Power Flow (OPF). The basic principal of an OPF is to optimize dispatch of power generation and voltage control actions to reach one or several objectives set by the user. Optimization requires various information to run, minimum being generation costs and dispatch ability for each generation units.

In the case of the Jamaica electricity grid, a complete merit order has been provided by JPS to the consultant. In addition with previously described choices of the consultant in modelling new units, this merit order allows the OPF to run simulations with the objective of minimizing generation costs, which is likely to be done in real operation. Voltage conditions are considered by the OPF as hard limits,

[3] Correlations with Winchester wind site are not used for first calculations.

meaning simulation cannot break any voltage limit at any bus in the network. The consultant has set two exceptions: one at Wigton and one at Winchester[4].

At Wigton, modelling of the transformers is such that violation of high voltage limit occurs very often and prevents the OPF to find a solution. This issue, if not only a modelling issue, is likely to find a simple solution by changing tap ratio of the step-up transformer in Wigton. The consultant has thus set this limit only as a reporting limit, meaning the OPF does not have to maintain it into acceptable range of variation, but report any violation of the limits.

At Winchester, with high possible generated power in some portfolio, voltage drop in the connection line and voltage conditions at the connecting bus, Annotto, can lead to high voltage limit violation. This limit has also been set to only "reporting limit".

Just as regular load-flow tools, an OPF tool requires all network parameters and inputs. Parameters were taken from previous mentioned adjusted model of Jamaica electricity grid. Inputs, such as unit engagement, solar and wind power and load, are provided by the probabilistic tool.

II.2.5. EDF tool

The probabilistic tool used by the consultant is based on EDF-developed tool created to perform any kind of uncertainty propagation study. This tool has been used by EDF throughout the years on several different types of problems, from nuclear safety to optimization of hydraulic facilities. The consultant has adapted it for the particular needs of the present consultancy services.

The basic principle of this tool is to generate relevant study cases, through an adjusted sampling method applied on a probabilistic model of the problem. Resulting samples are then sent to the simulation code, which returns simulation results to the tool. Analyses of the results are made partially directly by the probabilistic tool itself and with data-mining software for deeper investigation.

This probabilistic tool is property of EDF, is not commercialized and cannot be provided to any entity outside EDF. However, the consultant has decided to use the GNU General Public Licensed software package Orange, developed and maintained by the Bioinformatics Laboratory of the Faculty of Computer and Information Science, University of Ljubljana, Slovenia. In absence of commercial tool easily purchasable by the consultant and any Jamaican party, the consultant has decided with a PSS-E compatible tool. Together, these two choices will allow JPS and the Ministry of Science, Technology, Energy and Mining of Jamaica to read full results and investigate all simulated network situation easily themselves.

II.3. RESULTS

II.3.1. Steady-state performance of a network

The performance of a network, from a steady-state perspective, can be measured in many ways. The consultant has decided to use two criteria:

- The overloading criterion, defined as the ratio between the number of cases simulated with at least one line overloaded in the network and the total number of cases simulated;
- The voltage limit violation criterion, defined as the ratio between the number of cases simulated with at least one bus outside its normal voltage conditions in the network and the total number of cases simulated.

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[4] This approach is only valid if the system has the ability to manage the voltage in authorized limits. For 2030, this was not guaranteed and voltage limit violations have been allowed and monitored.

II.3.2. Steady-state operational safety in 2013 without additional renewable

The consultant has conducted simulations to calculate the performance criterion expected to serve as standard reference.

Simulations have been conducted based upon the probabilistic model previously described: the year has been divided into three periods, each period modelled through appropriate laws of probability, correlations and hydro flows. As for 2013 no solar power is used in Jamaica, at least not on a national-scale level, days and nights have not been differentiated.

For each period, 1000 N situations have been simulated. No overloading or voltage limit violation have been recorded.

For the same periods, 10 000 N-1 situations have been simulated. These situations are created from an N situation where one line is randomly set out of service. Lines of which outage would directly lead to load shedding or generation curtailment have not been considered, as their role is not relevant in this topic. None overloading or voltage limit violation have been recorded.

Criteria calculated by the consultant are at 0% in 2013 for both N and N-1 situations. These criteria are calculated as risks; the lower are the criteria the safer is the operation of the network. These results are in accordance with findings of previous Siemens PTI study conducted in July 2012.

These findings must not be misunderstood:

- As balancing is not in the scope of the study, the criteria focus on the network itself, disregarding generating unit availability. Should any generating unit outage cause major issue on the grid, it would not be relevant in assessing renewables impacts on the grid as impact of this unit on the grid would remain even with renewable. If, by chance, renewable potential was located sufficiently close to this critical unit to diminish its impact and act in a positive way on the criterion, it would still not be relevant to consider it, as renewables are not supposed to be commissioned in replacement of existing units but as new units. Any positive impacts renewable may have on the network in 2013 would need to be compared with equivalent addition of conventional generating units;
- Most of the peak-load machines are connected to the same buses as base-load or half-peak-load machines. Outage of any machines in the merit order is consequently considered not an issue from the network point of view. Matters of fuel supplies or N-2 units is disregarded;
- Line-trippings leading directly to load-shedding or generation curtailment are not considered since renewables cannot reduce their impact; renewables are not supposed to be implemented with frequency control capabilities enabling them to supply small electrical islands.

II.3.3. Steady-state operational safety in 2013 with renewable portfolio

The consultant has conducted similar simulations as previously described after implementing additional renewable sources as mentioned in Table II-8 and Table II-9.

Simulations have been conducted based upon the probabilistic model previously described: the year has been divided into three periods, each period modelled through appropriate laws of probability, correlations and hydro flows. As solar power is a significant part of the portfolio, days and nights have been separated. Results for nights are identical to section II.3.1.

For each day period, 1000 N situations have been simulated. None overloading or voltage limit violation have been recorded.

For the same periods, 10 000 N-1 situations have been simulated. These situations are created from an N situation where one line is randomly set out of service. Lines of which outage would directly lead to load shedding or generation curtailment have not been considered, as their role is not relevant in this topic. None overloading or voltage limit violation have been recorded.

These findings bring the conclusion that additional 370 GWh of solar power can be integrated in the Jamaica electricity grid without deteriorating its steady-state performance. Along with existing sites, it would lead to a penetration rate in energy of approximately 14.8%[5].

This figure is not the maximum penetration rate of renewables achievable on a short-term horizon, as the network is not likely to be a limiting factor. To increase this rate, the consultant would need to add new renewable sources to the simulated portfolio. Among all remaining sites from the selected portfolio for 2030, only Winchester is likely to be commissioned within a short period of time. This issue is discussed in the following section.

In addition, should the consultant decide to implement waste, biomass and new hydro projects in its 2013 portfolio, given their modelling as voltage controlled machines, these new units would directly come in replacement of existing with similar ancillary service capabilities. Under these conditions, those units are not likely to deteriorate the situation, given the steady-state margin noted by the consultant.

II.3.4. Winchester wind power site

The Winchester wind power site represents the largest potential for wind power in Jamaica. Preliminary survey, conducted by the German Wismar-based company Factor 4 Energy Projects GmbH and the Swiss Bern-based company Meteotest, shows exceptional capacity factor of 49%.

The Ministry of Science, Technology, Energy and Mining of Jamaica and the consultant have agreed to reduce this capacity factor in their calculations, to reduce the risk of further potential downward revision.

In portfolio 3, selected by the Ministry of Science, Technology, Energy and Mining of Jamaica, 60MW were suggested to be installed in Winchester, generating approximately 252 GWh. With discounted capacity factor to 40%, energy is likely to go down to 205 GWh.

However, its model being ready to install 106MW as suggested in portfolio 8, the consultant has decided to conduct extra simulations to give an insight of the situation to the Ministry of Science, Technology, Energy and Mining of Jamaica.

First conclusions of the consultant are that the network of Jamaica could accommodate approximately 70MW of new generation at Winchester wind site. Above this value, overloading of the Port Antonio – Annotto is likely to appear. With 106 MW installed at this location, as proposed in portfolio 8, probability of overloading of the line is slightly above 1%. Additional investment on the network would be required or energy would be curtailed.

The consultant suggests adjusting portfolio to install 70MW of new capacity at Winchester wind site. With a capacity factor of 40%, the wind farm would generate approximately 239 GWh and bringing the renewable penetration rate in 2013 to about 20.5%.

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[5] Total electricity consumption in 2013 is supposed to reach 4108 GWh.

II.4. TARGET FOR PENETRATION RATE ON A SHORT TERM HORIZON

From the network point of view, on a short term horizon, the Jamaica electricity grid has the ability to accommodate 20.5% of renewable energy without deteriorating its steady-state operational safety performance.

However, instantaneous penetration rate of wind and solar power together can reach relatively high figure. Below is given the cumulative density function of VRE (wind and solar power) share in total instantaneous generation.

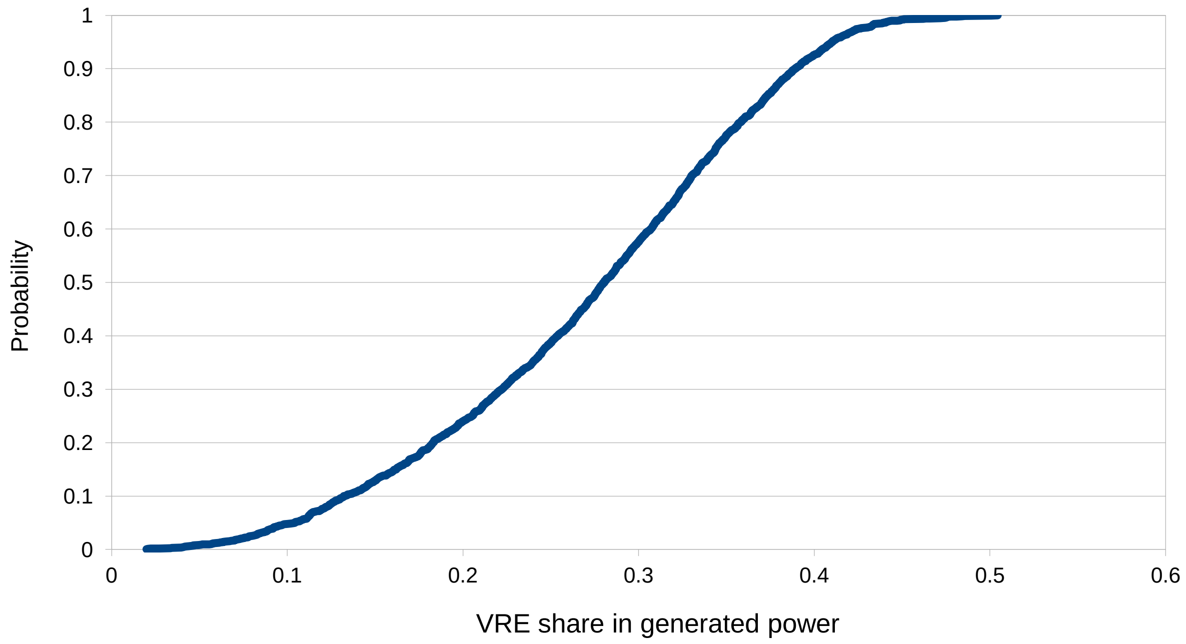

Figure II-1: cumulative density function of instantaneous VRE penetration rate during the day in 2013

It is very important to understand this figure: it gives the probability for VRE sources to generate some share of the total generated power at any time during the year. Probability for instantaneous VRE penetration rate to be higher than 30% during the year is higher than 40%.

Even if total share of renewable in energy will increase in the future, instantaneous penetration of VRE can only decrease[6]. Other renewables than VRE are not likely to cause any dynamic issue to the operation of the system by JPS. The consultant thus concludes that should addition of VRE capacity cause dynamic problems in operation, the situation would not remain for long. Increase in demand will be cover by controllable generating units and VRE instantaneous share will rapidly decrease. The dynamic issues are addressed in section 6 of this document.

[6] The portfolio n°3 selected by the MSTEM of Jamaica does not contain extra VRE sources outside of those implemented in this section.

III. CONSTRUCTION OF RENEWABLE ENERGY PORTFOLIOS

III.1. REACHING THE 30% RENEWABLES ELECTRICITY TARGET: RENEWABLE ENERGY PORTFOLIOS

In order to achieve its goal of 30% of total electricity generated from renewable energy sources by 2030, Jamaica is expected to install additional hydropower, biomass, waste-to-energy, wind and solar power plants to help satisfy its growing electricity demand. According to the Office of Utilities Regulation 2010 "Generation Expansion Plan", electricity demand in 2009 was 4.21 TWh [1]. Assuming a 2.5 % growth rate, demand in 2030 is expected to reach 7.08 TWh.

Thus, to achieve the 30% goal, 2.12 TWh of electricity must be generated from renewable sources of energy, to be allocated between hydropower, biomass, wind and solar photovoltaic and other resources.

III.1.1. Hydropower

The total hydropower potential of Jamaica is estimated by Hinicio to be 111.8 MW [2]. A breakdown by site is available in Table III-1. This table takes into account the extension of existing plant in Maggotty Falls.

Although all current and the vast majority of potential hydropower sites employ run-of-river technology, one potential site, Mahogany Vale, is a larger dam project. In order to calculate the total electrical energy per annum that can be expected from hydroelectric sources, an average capacity factor must be estimated. The average energy produced by the existing hydropower fleet (22.29 MW) for the period 1990-2009 was 117 GWh per year, according to the UN ECLAC report, "Renewable energies potential in Jamaica" [3]. Thus, an average capacity factor for run-of-river hydro of 59.9% can be estimated.

Assuming that all proposed and potential run-of-river sites are indeed developed by 2030, and taking the capacity factor for the proposed and potential run-of-river sites as equal to the average capacity factor of the existing fleet, the total expected energy output from run-of-river hydro sources is 324.4 GWh.

The Mahogany Vale prefeasibility report presents 5 different construction schemes, each with slightly different installed capacities and capacity factors. The recommended scenario involves a 50 MW installation with a capacity factor of 48.6%, for a total of 213 GWh annual output, although two alternative, lower cost and lower impact schemes are also retained for further consideration, resulting in 40 and 46 MW projects with 45.1% and 48.6% capacity factors, respectively [4].

For the purposes of this study, we will assume that if the dam is build, the recommended scenario will be adopted. Thus, the maximum potential hydroelectric power contribution in 2030 is 585.5 GWh.

New information has been transmitted to the consultant at the end of the final assignment in Jamaica: the dam is exclusive of 6 other run-of-river projects[7]. Excluding these projects leads to a maximum hydropower potential of 491.6 GWh. Because this information was received at the end of the study, the relevant modifications do not appear on the scenarios presented in this chapter. However, they are taken into consideration in the report starting from chapter III.3 – Portfolio Selected by the MSTEM.

[7] The dam will not be built but the 6 run-of-river projects will. The selected portfolio has been updated later in the document. This new portfolio does not reach the objective of 30% of renewable in electricity generation.

Site	Status	Technology	Capacity (MW)	Capacity Factor	Annual Production (GWh)
Rio Bueno A	existing	run-of-river	2,5	60%	13,1
Rio Bueno B	existing	run-of-river	1,1	60%	5,8
Maggoty Falls	extension	run-of-river	12,6	60%	66,1
Upper White River	existing	run-of-river	3,8	60%	19,9
Lower White River	existing	run-of-river	4	60%	21,0
Roaring River	existing	run-of-river	3,8	60%	19,9
Constant Spring	existing	run-of-river	0,8	60%	4,2
Ram's Horn	existing	run-of-river	0,6	60%	3,1
Great River	proposed	run-of-river	8	60%	42,0
Laughlands	proposed	run-of-river	2	60%	10,5
Back Rio Grande	proposed	run-of-river	10	60%	52,5
Green River	potential	run-of-river	1,4	60%	7,3
Martha Brae	potential	run-of-river	12,6	33%	36,4
Rio Cobre	potential	run-of-river	2	30%	5,2
Dry River	potential	run-of-river	0,8	60%	4,2
Negro River	potential	run-of-river	2,5	34%	7,5
Yallahs River	potential	run-of-river	2,6	60%	13,6
Wild Cane River	potential	run-of-river	2,5	60%	13,1
Morgan's River	potential	run-of-river	2,7	34%	8,1
Spanish River	potential	run-of-river	7,7	28%	18,6
Mahogany Vale	potential	dam	50	49%	213
		Total	111,8		585,5

Table III-1: Potential Hydropower Sites and Annual Production for 2030

III.1.2. Biomass

Two pathways of electricity generation from biomass were identified in the UN ECLAC report on Jamaica's renewable energy potentials: cogeneration in Sugar Corporation of Jamaica Mills, and waste treatment [3]. Six sugar mills have been preselected for cogeneration, with an estimate total capacity of 85 MW [5]. Assuming that the high-pressure (40 bar) technology is selected, cogeneration at these sites is expected to be able to generate up to 396.4 GWh [5].

As for the waste treatment pathway, two potential sites are feasible by 2030: one in Kingston (Riverton), one in Montego Bay (Retirement) [6]. The expected installed capacities of the two sites are 45 and 20 MW, for a total annual energy production of 301.6 and 134 GWh, respectively [6]. Thus, the maximum total potential annual energy contribution from biomass sources is estimated at 842.5 GWh. A summary of potential biomass energy production for 2030 is provided in Table 2.

Site	Technology	Installed Capacity (MW)	Capacity Factor	Annual Production (GWh)
Golden Grove	Cogeneration	8	48%	33.6
Everglades	Cogeneration	5	56%	24.5
Appleton	Cogeneration	20	61%	106.9
Worthy Park	Cogeneration	10	55%	48.2
Monymusk	Cogeneration	15	52%	68.3
Frome	Cogeneration	27	53%	125.4
Riverton	Waste	45	77%	301.6
Retirement	Waste	20	77%	134.0
			Total	842.5

Table III-2: Potential electricity production from biomass for 2030

III.1.3. Wind

The E/NE trade winds characterize the principal wind regime in Jamaica. As Jamaica's vegetation is generally dense outside of city centres, the best potential wind sites are thus hill or mountain crests perpendicular to these prevailing winds.

The current Wigton wind farms I and II are located on such a crest, for a total of 38.7 MW [7]. The current JPS-owned Munro wind farm of 4x0.75MW turbines for a total of 3MW is also situated on such a crest; a 20 unit (15 MW) extension is planned [7]. To search for further potential wind sites, Wigton commissioned AWS Truewind to perform a wind resource assessment of the entire island. The resulting report, "Wind Resource Maps of Jamaica" locates 7 of such crests, oriented N/NW to S/SE, with high average wind speeds [8].

These regions were further explored in search of plots of land suitable for wind farm development. Wigton chose 18 of the most promising sites for further study. Anemometers, wind vanes, and data loggers were installed at each site and measurements commenced in November of 2011. Though 12 months of measurements were planned, a pre-analysis of the data was presented after 6 months of collection, and preliminary results were discussed [7].

The 5 top ranked sites include 4 in the south-eastern part of the country (Rose Hill, Top Lincoln, Kemps Hill, and Fair Mountain), and one in the John Crow Mountains (Winchester). The Fair Mountain site will most likely not be developed by Wigton unless financial or political incentives change in the near future, as the vegetation is particularly high on-site, and the open areas available for development are at a lower elevation than measurements were made. The Top Lincoln site was considered promising, but due to the proximity to the existing Munro farm and the potential conflict of interest in the case of a Munro extension, the site was abandoned.

However, the other 3 sites will most likely be developed by Wigton. The available area at each site translates to a range of possible installation capacities, and at certain sites a more thorough analysis of wind turbine placement was performed to give a better estimate of the installed capacity of a potential Wigton farm. From these estimates, a maximum and a minimum installation capacity was selected for each of the 5 potential sites; for the 2 sites abandoned by Wigton, the minimum was taken to be 0 MW, as development at these sites is less certain.

A summary of the potential wind farm sites for 2030 and their capacities is provided in Table 3. As for the Rose Hill and Winchester sites, it is important to note that the capacity factors chosen for the study (respectively 35% and 40%) are intentionally lower than the numbers that were found in the literature (respectively 40.1% and 47.9%) and considered as suspiciously high by the consultant team, that has opted for a conservative approach.

Site	Status	Capacity (MW)		Capacity Factor	Annual Energy (GWh)	
		Min	Max		Min	Max
Wigton I	existing	20,7	20,7	30,0%	54,4	54,4
Wigton II	existing	18	18	37,5%	59,1	59,1
Munro	existing	3	3	28,5%	7,5	7,5
Rose Hill	proposed	30	30	35,0%	92,0	92,0
Munro II	proposed	15	15	28,5%	37,4	37,4
Top Lincoln	potential	0	12	32,6%	0,0	34,3
Fair Mountain	potential	0	50	22,5%	0,0	98,4
Kemps Hill	potential	16	300	10,3%	14,4	270,7
Winchester	potential	60	280	40,0%	210,2	981,1
				Total	475,1	1634,9

Table III-3: Potential Wind Farm Sites and their Estimated Annual Production

In order to calculate the expected energy output for each of these sites, the capacity factor is needed. The capacity factor depends on both the wind profile of the site at the hub height of installed wind turbines, and the choice of turbine. For the Munro I and II sites equipped with small, 750 kW turbines, a capacity factor of 28.5% is assumed, based on the annual energy production estimate for the existing Munro farm available from The Wind Power online database [9].

With 900 kW turbines, Wigton I's capacity factor is estimated at 30%, whereas the larger 2MW Vestas V80 turbines installed at the Wigton II farm account for an increased capacity factor of about 37.5% [7]. For the remaining sites, installation of 2 MW turbines similar to the V80 turbines at Wigton II was assumed for purposes of energy output estimations. At each site, the wind speed was measured at 3 heights; the vertical wind profile was then characterized and the wind speed at 79 m (hub height of the V80) was extrapolated. The annual energy output of a single 2 MW V80 turbine was then estimated for each site. The histogram of the resulting time series of 6-months of projected 79 m wind speeds was multiplied by the wind speed to power transfer function of the V80 wind turbine, and the summed total was extrapolated over the entire year. To calculate the capacity factor, the estimated annual production of a single turbine is divided by the theoretical output of a 2 MW generator running at rated power. The resulting capacity factors and estimated annual energy outputs corresponding to the minimum and maximum installed capacities for each site are also included in Table 3. The total annual production from centralized wind farms can thus be expected to fall within a range of 530.1 to 1842.1 GWh.

Although it would be possible to incentivize the installation of distributed wind generation, it is known that the efficiency of smaller wind turbines is considerably less than that of centralized production. Additionally, when small wind turbines are installed on rooftops in metropolitan areas, the level of turbulence and the greater number of obstacles result in a degraded wind profile. Thus, it is recommended that since the 30% renewable energy target can be met by other means, that a distributed wind energy strategy should not be employed.

III.1.4. Solar Photovoltaic

The choice of potential sites for centralized PV production for 2030 was taken from a list of feasible sites provided by Ansel Garvey of A.S.C. Garvey & Associates, Ltd, selected based on size, availability, access, topographic, and zoning criteria [10]. The potential installed capacity of each site was determined either by calculating the total capacity that could be installed within available area of the site8, or by the capacities proposed by existing bids for solar power plant development. When the capacity based on total area and the bid value did not coincide, the former was taken to be the maximum possible capacity and the latter to define the minimum capacity value.

Similar to wind energy, distributed solar PV is often less efficient than centralized solar PV power plants, as orientation cannot always be optimized, and minimization of shading and soiling is less certain. Thus, as long as centralized hydro, biomass, wind and solar installations can satisfy the 30% target, distributed solar PV should not be considered.

To calculate the expected energy contribution for each centralized PV site, the average annual global horizontal irradiance and direct normal irradiance values corresponding to each location were taken from the "Solar Irradiance Map of Jamaica" [11]. Next, the production of a "typical centralized" solar plant was simulated for each hour of the year for each site, assuming that the GHI and DNI values constant and equal to the annual average.

An albedo of 0.29, a shading and soiling loss factor of 2%, a wind-speed of 3m/s10, an atmospheric pressure of 100 kPa, and the temperature profile of a typical site were assumed representative of the island. The models developed at the US Department of Energy's Sandia National Laboratory for PV array and inverter performance estimation [12], as well as the Hay-Davies model for transposition of measured irradiance values to the plane of array [13], were implemented to perform the simulation.

The Aleo multicrystalline silicon S16 175W module was selected for simulation, as it had already been selected for the site assessments performed and included with the solar irradiance map [11]. The "typical centralized" solar plant modelled was an array of 640 of such panels, 16 in series and 40 in parallel, facing south and optimally inclined at an angle equal to the site's latitude, and connected to a Xantrex GT100kW-480V inverter. The minimal and maximal production estimates for each site were calculated by normalizing the annual production estimate of the "typical" installation by its capacity and multiplying by the minimal and maximal expected capacities for 2030. The total centralized solar PV potential can be thus estimated at 936.6 to 957.0 GWh. The list of potential solar power plant sites and their expected annual generation is provided in Table 4.

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[8] It was assumed that 6 acres were needed per MW of installed PV capacity.
[9] The default albedo value used in PVSyst, a reference software for PV performance modeling.
[10] Also the PVSyst default value.

Site	Installed Capacity (MW)				Radiation (W/m^2)		Capacity	Location		Total Energy (GWh)	
	Bid	Potential	Min	Max	avg GHI	avg DNI	Factor	Latitude	Longitude	Low	Hi
Orange Bay	20	25	20	25	218.6	192.1	20.9%	18.34	-78.33	36.6	45.8
Paradise 1	49.5	49.5	49.5	49.5	225.5	201.9	21.5%	18.21	-78.09	93.2	93.2
Paradise 2	30	30	30	35	225.5	201.9	21.5%	18.21	-78.09	56.5	65.9
Duncan	-	30	30	30	222.4	198.9	21.2%	18.44	-77.53	55.7	55.7
Good Year	25	25	25	25	223.2	197.1	21.3%	17.88	-76.37	46.6	46.6
Golden Grove	-	49.5	30	30	223.2	179.6	21.2%	17.91	-76.27	55.7	55.7
Old Harbour	44	43	43	44	222.6	195.4	21.2%	17.94	-77.07	79.9	81.7
Kelly's Pen A	20	-	20	20	230.3	209.6	21.9%	17.91	-77.13	38.4	38.4
Kelly's Pen B	-	50	50	50	230.3	209.6	21.9%	17.91	-77.13	95.9	95.9
Spring Village	20	-	20	20	221.2	194.8	21.1%	17.98	-77.03	37.0	37.0
Windsor	-	49.5	49.5	49.5	233.7	216.4	22.1%	17.91	-76.93	95.8	95.8
Micham	25	25	25	25	221.5	191.7	21.1%	18.04	-77.60	46.2	46.2
Toll Gate	20	-	20	20	216.9	185.5	20.7%	17.98	-77.36	36.3	36.3
Parnassus	43	-	43	43	222.9	195.7	21.3%	17.94	-77.33	80.2	80.2
Race Course	-	43	43	43	231.1	209.3	21.9%	17.85	-77.33	82.5	82.5
									Total	936.6	957.0

Table III-4: List of expected solar power plant sites for 2030 and total annual production estimates

III.1.5. Energy Totals

The maximum possible contribution of hydropower, biomass, and centralized wind and solar power is estimated between 2.3 and 3.9 TWh (see Table 6). As only 2.12 TWh are necessary in order to achieve the 30% target, a set of portfolios producing at least 2.12 TWh from different allocations of renewable energy sources was selected. An economic analysis of each portfolio was then performed.

	Annual Production (GWh)	
Source	Low	High
Hydropower	368,3	491,6
Biomass/Waste	550,2	842,5
Centralized Wind	475,8	1634,9
Centralized Solar	936,6	957,0
Total	2331	3926

Table III-5: Total renewable electricity potential for Jamaica

Based on the renewable resource assessment performed in the previous sections, seven contrasted renewable energy portfolios have been constructed for the year 2030. For that purpose, it seemed useful to classify renewable energies into two broad categories: non-intermittent (base load) and intermittent renewables.

The latter include wind and solar, which can have very strong variations in output in a matter of hours, minutes and even seconds. On the other hand, base-load renewable energies include waste-to-energy power plants, biomass power plants and hydropower plants.

Strictly speaking, hydropower should be further divided into two subcategories, reservoir hydro (hydro dam) and run-of-river hydro. Hydro dams have large storage capacities and are generally considered as totally dispatchable as a consequence. In contrast, run-of-river power plants have no or only a very limited storage capacity. Additionally, their output is highly dependent on water flow rate, which may vary seasonally or annually in function of rainfall patterns. However, these variations are much easier to forecast and manage from the grid operator standpoint compared to those of wind and solar. Therefore, for the sake of the study all hydro power plants will be considered as being part of the base load.

The following table explains how the seven scenarios have been developed. In all seven cases, the overarching objective is to reach an annual 2.12TWh of renewable electricity by 2030. Each portfolio describes a potential snapshot of the Jamaican electricity mix in 2030. At this stage, however, the trajectory from 2013 through 2030 has not been defined. This final task will be completed in the next phase of the study, but only for the selected portfolio.

	Solar PV	Wind	Wind and solar PV
High base-load	Portfolio 1	Portfolio 2	Portfolio 3
No base-load	Impossible	Impossible	Portfolio 4
Low base-load	Portfolio 6	Portfolio 5	Portfolio 7

The portfolios are characterized by both their level of base-load capacity and by the nature and quantity of the intermittent renewables that complete the profiles such that the 2.12TWh objective is attained. All of these scenarios were presented to the MSTEM. The final selected scenario is presented later in the document.

The high base-load scenario (second line of the table) corresponds to the situation where the biomass, hydro and waste resources previously identified would be employed at their maximum potentials in 2030, representing 1.34TWh on an annual basis. However, about 0.74TWh would still be needed to achieve the 2.12TWh renewable target. That gap could be filled either with 100% of solar PV (portfolio 1), 100% of wind power (portfolio 2) or a combination of both (portfolio 3).

We also looked at a second range of potential portfolios with larger amounts of intermittent power and a smaller share of base-load production. In this “low base-load” set of scenarios, biomass, hydro and waste-to-energy power plants combined would only produce 0.93TWh per annum. Compared to the “high base-load” set of scenarios, we assumed that neither the Mahogany Vale hydro project nor the smallest biomass and waste-to-energy projects (namely Golden Grove, Everglades, Worthy Park and Retirement) would be implemented before 2030. Likewise, the remaining 1.19TWh can be supplied either by solar PV (portfolio 6), wind (portfolio 5) or a combination of both (portfolio 7).

Finally, one last scenario has been envisaged, where no base-load production was included (except the hydro plants already in operation in 2013). In such a case, the entire renewable energy target of 2.12TWh would have to be achieved with intermittent wind and/or solar PV production. The overall wind and solar potential being both below that total, the portfolios based only on wind or solar PV would fall short of the target and are therefore ruled out as infeasible., Thus, only a portfolio based on 50% wind and 50% solar PV is considered (portfolio 4)[11].

III.1.6. Proposed renewable energy portfolios

The following tables describe each of the seven proposed portfolios. Plants already in operation in 2013 are marked in dark blue.

[11] All scenarios include the renewable capacities already in operation at the time of writing, such as the Wigton I, Wigton II and Munro wind farm as well as the existing run-of-river hydro power plants. As a consequence, even the portfolios 1 and 6 contain small amounts of wind power. Similarly, portfolio 4 does include the already existing hydro plants. Only the selected portfolio has been updated according the last available information.

Portfolio 1 (High base load / Solar PV):

Technology	Site_Name	Capacity (MW)	Capacity factor	Annual Energy Output (GWh)
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	8	0,60	41,98
Hydro run-of-river	Laughlands	2	0,60	10,49
Hydro run-of-river	Back Rio Grande	10	0,60	52,47
Hydro run-of-river	Green River	1,4	0,60	7,35
Hydro run-of-river	Martha Brae	4,8	0,60	25,19
Hydro run-of-river	Rio Cobre	1	0,60	5,25
Hydro run-of-river	Dry River	0,8	0,60	4,20
Hydro run-of-river	Negro River	1	0,60	5,25
Hydro run-of-river	Yallahs River	2,6	0,60	13,64
Hydro run-of-river	Wild Cane River	2,5	0,60	13,12
Hydro run-of-river	Morgan's River	2,3	0,60	12,07
Hydro run-of-river	Spanish River	2,5	0,60	13,12
Hydro dam	Mahogany Vale	50	0,49	212,87
Waste	Riverton	45	0,77	301,56
Waste	Retirement	20	0,77	134,03
PV	Orange Bay	25	0,21	45,77
PV	Paradise 1	0	0,22	93,23
PV	Paradise 2	0	0,22	56,50
PV	Duncan	0	0,21	0,00
PV	Good Year	0	0,21	46,65
PV	Golden Grove	0	0,21	0,00
PV	Old Harbour	0	0,21	81,71
PV	Kelly's Pen A	0	0,22	38,37
PV	Kelly's Pen B	50	0,22	95,92
PV	Spring Village	0	0,21	36,97
PV	Windsor	0	0,22	0,00
PV	Micham	0	0,21	46,21
PV	Toll Gate	0	0,21	0,00
PV	Parnassus	0	0,21	80,23
PV	Race Course	0	0,22	0,00
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	0	0,35	0,00
Wind	Munro	3	0,29	7,49
Wind	Munro II	0	0,29	0,00
Wind	Top Lincoln	0	0,33	0,00
Wind	Fair Mountain	0	0,22	0,00
Wind	Kemps Hill	0	0,10	0,00
Wind	Winchester	0	0,40	0,00
Biomass Cogeneration	Golden Grove	9	0,48	37,84
Biomass Cogeneration	Everglades	4,5	0,56	22,08
Biomass Cogeneration	Appleton	20,5	0,61	109,54
Biomass Cogeneration	Worthy Park	9,5	0,55	45,77
Biomass Cogeneration	Monymusk	15	0,52	68,33
Biomass Cogeneration	Frome	27,5	0,53	127,68
			TOTAL	2,12

Portfolio 2 (High base-load / Wind):

Technology	Site_Name	Selected Capacity (MW)	Capacity factor	Annual Energy Output (GWh)
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	8	0,60	41,98
Hydro run-of-river	Laughlands	2	0,60	10,49
Hydro run-of-river	Back Rio Grande	10	0,60	52,47
Hydro run-of-river	Green River	1,4	0,60	7,35
Hydro run-of-river	Martha Brae	4,8	0,60	25,19
Hydro run-of-river	Rio Cobre	1	0,60	5,25
Hydro run-of-river	Dry River	0,8	0,60	4,20
Hydro run-of-river	Negro River	1	0,60	5,25
Hydro run-of-river	Yallahs River	2,6	0,60	13,64
Hydro run-of-river	Wild Cane River	2,5	0,60	13,12
Hydro run-of-river	Morgan's River	2,3	0,60	12,07
Hydro run-of-river	Spanish River	2,5	0,60	13,12
Hydro dam	Mahogany Vale	50	0,49	212,87
Waste	Riverton	45	0,77	301,56
Waste	Retirement	20	0,77	134,03
PV	Orange Bay	0	0,21	0,00
PV	Paradise 1	0	0,22	0,00
PV	Paradise 2	0	0,22	0,00
PV	Duncan	0	0,21	0,00
PV	Good Year	0	0,21	0,00
PV	Golden Grove	0	0,21	0,00
PV	Old Harbour	0	0,21	0,00
PV	Kelly's Pen A	0	0,22	0,00
PV	Kelly's Pen B	0	0,22	0,00
PV	Spring Village	0	0,21	0,00
PV	Windsor	0	0,22	0,00
PV	Micham	0	0,21	0,00
PV	Toll Gate	0	0,21	0,00
PV	Parnassus	0	0,21	0,00
PV	Race Course	0	0,22	0,00
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	30	0,35	91,98
Wind	Munro	3	0,29	7,49
Wind	Munro II	15	0,29	37,45
Wind	Top Lincoln	12	0,33	34,26
Wind	Fair Mountain	10	0,22	19,67
Wind	Kemps Hill	0	0,10	0,00
Wind	Winchester	125	0,40	438,00
Biomass Cogeneration	Golden Grove	9	0,48	37,84
Biomass Cogeneration	Everglades	4,5	0,56	22,08
Biomass Cogeneration	Appleton	20,5	0,61	109,54
Biomass Cogeneration	Worthy Park	9,5	0,55	45,77
Biomass Cogeneration	Monymusk	15	0,52	68,33
Biomass Cogeneration	Frome	27,5	0,53	127,68
			TOTAL	2,12

Portfolio 3 (High base load / Wind and solar PV):

Technology	Site_Name	Selected Capacity	Capacity factor	Annual Energy
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	8	0,60	41,98
Hydro run-of-river	Laughlands	2	0,60	10,49
Hydro run-of-river	Back Rio Grande	10	0,60	52,47
Hydro run-of-river	Green River	1,4	0,60	7,35
Hydro run-of-river	Martha Brae	4,8	0,60	25,19
Hydro run-of-river	Rio Cobre	1	0,60	5,25
Hydro run-of-river	Dry River	0,8	0,60	4,20
Hydro run-of-river	Negro River	1	0,60	5,25
Hydro run-of-river	Yallahs River	2,6	0,60	13,64
Hydro run-of-river	Wild Cane River	2,5	0,60	13,12
Hydro run-of-river	Morgan's River	2,3	0,60	12,07
Hydro run-of-river	Spanish River	2,5	0,60	13,12
Hydro dam	Mahogany Vale	50	0,49	212,87
Waste	Riverton	45	0,77	301,56
Waste	Retirement	20	0,77	134,03
PV	Orange Bay	0	0,21	0,00
PV	Paradise 1	49,5	0,22	93,23
PV	Paradise 2	30	0,22	56,50
PV	Duncan	0	0,21	0,00
PV	Good Year	0	0,21	0,00
PV	Golden Grove	0	0,21	0,00
PV	Old Harbour	30	0,21	55,71
PV	Kelly's Pen A	20	0,22	38,37
PV	Kelly's Pen B	0	0,22	0,00
PV	Spring Village	0	0,21	0,00
PV	Windsor	0	0,22	0,00
PV	Micham	25	0,21	46,21
PV	Toll Gate	0	0,21	0,00
PV	Parnassus	43	0,21	80,23
PV	Race Course	0	0,22	0,00
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	0	0,35	0,00
Wind	Munro	3	0,29	7,49
Wind	Munro II	0	0,29	0,00
Wind	Top Lincoln	0	0,33	0,00
Wind	Fair Mountain	0	0,22	0,00
Wind	Kemps Hill	0	0,10	0,00
Wind	Winchester	72	0,40	252,29
Biomass Cogeneration	Golden Grove	9	0,48	37,84
Biomass Cogeneration	Everglades	4,5	0,56	22,08
Biomass Cogeneration	Appleton	20,5	0,61	109,54
Biomass Cogeneration	Worthy Park	9,5	0,55	45,77
Biomass Cogeneration	Monymusk	15	0,52	68,33
Biomass Cogeneration	Frome	27,5	0,53	127,68
			TOTAL	2,12

Portfolio 4 (No base-load / Wind and solar PV):

Technology	Site_Name	Selected Capacity	Capacity factor	Annual Energy
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	0	0,60	0,00
Hydro run-of-river	Laughlands	0	0,60	0,00
Hydro run-of-river	Back Rio Grande	0	0,60	0,00
Hydro run-of-river	Green River	0	0,60	0,00
Hydro run-of-river	Martha Brae	0	0,60	0,00
Hydro run-of-river	Rio Cobre	0	0,60	0,00
Hydro run-of-river	Dry River	0	0,60	0,00
Hydro run-of-river	Negro River	0	0,60	0,00
Hydro run-of-river	Yallahs River	0	0,60	0,00
Hydro run-of-river	Wild Cane River	0	0,60	0,00
Hydro run-of-river	Morgan's River	0	0,60	0,00
Hydro run-of-river	Spanish River	0	0,60	0,00
Hydro dam	Mahogany Vale	0	0,49	0,00
Waste	Riverton	0	0,77	0,00
Waste	Retirement	0	0,77	0,00
PV	Orange Bay	25	0,21	45,77
PV	Paradise 1	49,5	0,22	93,23
PV	Paradise 2	30	0,22	56,50
PV	Duncan	0	0,21	0,00
PV	Good Year	25	0,21	46,65
PV	Golden Grove	49,5	0,21	91,93
PV	Old Harbour	44	0,21	81,71
PV	Kelly's Pen A	20	0,22	38,37
PV	Kelly's Pen B	50	0,22	95,92
PV	Spring Village	20	0,21	36,97
PV	Windsor	49,5	0,22	95,83
PV	Micham	25	0,21	46,21
PV	Toll Gate	20	0,21	36,27
PV	Parnassus	43	0,21	80,23
PV	Race Course	43	0,22	82,49
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	30	0,35	91,98
Wind	Munro	3	0,29	7,49
Wind	Munro II	15	0,29	37,45
Wind	Top Lincoln	12	0,33	34,26
Wind	Fair Mountain	45	0,22	88,53
Wind	Kemps Hill	0	0,10	0,00
Wind	Winchester	200	0,40	700,80
Biomass Cogeneration	Golden Grove	0	0,48	0,00
Biomass Cogeneration	Everglades	0	0,56	0,00
Biomass Cogeneration	Appleton	0	0,61	0,00
Biomass Cogeneration	Worthy Park	0	0,55	0,00
Biomass Cogeneration	Monymusk	0	0,52	0,00
Biomass Cogeneration	Frome	0	0,53	0,00
			TOTAL	2,12

Portfolio 5 (Low base-load / Wind):

Technology	Site_Name	Capacity (MW)	Capacity factor	Annual Energy Output (GWh)
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	8	0,60	41,98
Hydro run-of-river	Laughlands	2	0,60	10,49
Hydro run-of-river	Back Rio Grande	10	0,60	52,47
Hydro run-of-river	Green River	1,4	0,60	7,35
Hydro run-of-river	Martha Brae	4,8	0,60	25,19
Hydro run-of-river	Rio Cobre	1	0,60	5,25
Hydro run-of-river	Dry River	0,8	0,60	4,20
Hydro run-of-river	Negro River	1	0,60	5,25
Hydro run-of-river	Yallahs River	2,6	0,60	13,64
Hydro run-of-river	Wild Cane River	2,5	0,60	13,12
Hydro run-of-river	Morgan's River	2,3	0,60	12,07
Hydro run-of-river	Spanish River	2,5	0,60	13,12
Hydro dam	Mahogany Vale	0	0,49	0,00
Waste	Riverton	45	0,77	301,56
Waste	Retirement	0	0,77	0,00
PV	Orange Bay	0	0,21	0,00
PV	Paradise 1	0	0,22	0,00
PV	Paradise 2	0	0,22	0,00
PV	Duncan	0	0,21	0,00
PV	Good Year	0	0,21	0,00
PV	Golden Grove	0	0,21	0,00
PV	Old Harbour	0	0,21	0,00
PV	Kelly's Pen A	0	0,22	0,00
PV	Kelly's Pen B	0	0,22	0,00
PV	Spring Village	0	0,21	0,00
PV	Windsor	0	0,22	0,00
PV	Micham	0	0,21	0,00
PV	Toll Gate	0	0,21	0,00
PV	Parnassus	0	0,21	0,00
PV	Race Course	0	0,22	0,00
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	30	0,35	91,98
Wind	Munro	3	0,29	7,49
Wind	Munro II	15	0,29	37,45
Wind	Top Lincoln	12	0,33	34,26
Wind	Fair Mountain	50	0,22	98,37
Wind	Kemps Hill	50	0,10	45,12
Wind	Winchester	220	0,40	770,88
Biomass Cogeneration	Golden Grove	0	0,48	0,00
Biomass Cogeneration	Everglades	0	0,56	0,00
Biomass Cogeneration	Appleton	20,5	0,61	109,54
Biomass Cogeneration	Worthy Park	0	0,55	0,00
Biomass Cogeneration	Monymusk	15	0,52	68,33
Biomass Cogeneration	Frome	27,5	0,53	127,68
			TOTAL	2,12

Portfolio 6 (Low base-load / Solar PV):

Note: in this portfolio, the solar PV potential is fully exploited but fails to entirely fill the gap to reach the 30% renewable energy target. 30MW of wind power had therefore to be added.

Technology	Site_Name	Capacity (MW)	Capacity factor	Annual Energy Output (GWh)
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	8	0,60	41,98
Hydro run-of-river	Laughlands	2	0,60	10,49
Hydro run-of-river	Back Rio Grande	10	0,60	52,47
Hydro run-of-river	Green River	1,4	0,60	7,35
Hydro run-of-river	Martha Brae	4,8	0,60	25,19
Hydro run-of-river	Rio Cobre	1	0,60	5,25
Hydro run-of-river	Dry River	0,8	0,60	4,20
Hydro run-of-river	Negro River	1	0,60	5,25
Hydro run-of-river	Yallahs River	2,6	0,60	13,64
Hydro run-of-river	Wild Cane River	2,5	0,60	13,12
Hydro run-of-river	Morgan's River	2,3	0,60	12,07
Hydro run-of-river	Spanish River	2,5	0,60	13,12
Hydro dam	Mahogany Vale	0	0,49	0,00
Waste	Riverton	45	0,77	301,56
Waste	Retirement	0	0,77	0,00
PV	Orange Bay	0	0,21	45,77
PV	Paradise 1	0	0,22	93,23
PV	Paradise 2	0	0,22	56,50
PV	Duncan	20	0,21	37,14
PV	Good Year	0	0,21	46,65
PV	Golden Grove	49,5	0,21	91,93
PV	Old Harbour	0	0,21	81,71
PV	Kelly's Pen A	0	0,22	38,37
PV	Kelly's Pen B	50	0,22	95,92
PV	Spring Village	0	0,21	36,97
PV	Windsor	49,5	0,22	95,83
PV	Micham	0	0,21	46,21
PV	Toll Gate	0	0,21	36,27
PV	Parnassus	0	0,21	80,23
PV	Race Course	43	0,22	82,49
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	0	0,35	0,00
Wind	Munro	3	0,29	7,49
Wind	Munro II	0	0,29	0,00
Wind	Top Lincoln	0	0,33	0,00
Wind	Fair Mountain	0	0,22	0,00
Wind	Kemps Hill	0	0,10	0,00
Wind	Winchester	30	0,40	105,12
Biomass Cogeneration	Golden Grove	0	0,48	0,00
Biomass Cogeneration	Everglades	0	0,56	0,00
Biomass Cogeneration	Appleton	20,5	0,61	109,54
Biomass Cogeneration	Worthy Park	0	0,55	0,00
Biomass Cogeneration	Monymusk	15	0,52	68,33
Biomass Cogeneration	Frome	27,5	0,53	127,68
			TOTAL	2,12

Portfolio 7 (Low base-load / Wind and solar PV):

Technology	Site_Name	Selected Capacity	Capacity factor	Annual Energy
Hydro run-of-river	Rio Bueno A	2,5	0,60	13,12
Hydro run-of-river	Maggoty Falls	6,3	0,60	33,06
Hydro run-of-river	Upper White River	3,8	0,60	19,94
Hydro run-of-river	Lower White River	4	0,60	20,99
Hydro run-of-river	Roaring River	3,8	0,60	19,94
Hydro run-of-river	Constant Spring	0,8	0,60	4,20
Hydro run-of-river	Ram's Horn	0,6	0,60	3,15
Hydro run-of-river	Great River	8	0,60	41,98
Hydro run-of-river	Laughlands	2	0,60	10,49
Hydro run-of-river	Back Rio Grande	10	0,60	52,47
Hydro run-of-river	Green River	1,4	0,60	7,35
Hydro run-of-river	Martha Brae	4,8	0,60	25,19
Hydro run-of-river	Rio Cobre	1	0,60	5,25
Hydro run-of-river	Dry River	0,8	0,60	4,20
Hydro run-of-river	Negro River	1	0,60	5,25
Hydro run-of-river	Yallahs River	2,6	0,60	13,64
Hydro run-of-river	Wild Cane River	2,5	0,60	13,12
Hydro run-of-river	Morgan's River	2,3	0,60	12,07
Hydro run-of-river	Spanish River	2,5	0,60	13,12
Hydro dam	Mahogany Vale	0	0,49	0,00
Waste	Riverton	45	0,77	301,56
Waste	Retirement	0	0,77	0,00
PV	Orange Bay	20	0,21	36,62
PV	Paradise 1	49,5	0,22	93,23
PV	Paradise 2	30	0,22	56,50
PV	Duncan	0	0,21	0,00
PV	Good Year	15	0,21	27,99
PV	Golden Grove	0	0,21	0,00
PV	Old Harbour	44	0,21	81,71
PV	Kelly's Pen A	20	0,22	38,37
PV	Kelly's Pen B	0	0,22	0,00
PV	Spring Village	20	0,21	36,97
PV	Windsor	0	0,22	0,00
PV	Micham	25	0,21	46,21
PV	Toll Gate	20	0,21	36,27
PV	Parnassus	43	0,21	80,23
PV	Race Course	0	0,22	0,00
Wind	Wigton I	20,7	0,30	54,40
Wind	Wigton II	18	0,38	59,13
Wind	Rose Hill	30	0,35	91,98
Wind	Munro	3	0,29	7,49
Wind	Munro II	10	0,29	24,97
Wind	Top Lincoln	0	0,33	0,00
Wind	Fair Mountain	0	0,22	0,00
Wind	Kemps Hill	0	0,10	0,00
Wind	Winchester	120	0,40	420,48
Biomass	Golden Grove	0	0,48	0,00
Biomass	Everglades	0	0,56	0,00
Biomass	Appleton	20,5	0,61	109,54
Biomass	Worthy Park	0	0,55	0,00
Biomass	Monymusk	15	0,52	68,33
Biomass	Frome	27,5	0,53	127,68
			TOTAL	2,12

The following chart summarizes the renewable capacities installed in each of the portfolios (renewable power plants already in operation have not been included). Unsurprisingly, the total amount of renewable power to be installed in each scenario varies quite substantially from a low 400MW in the second portfolio to over 700MW in the fourth portfolio. This is a direct result of the differences in capacity factors. Solar PV generally has the lowest capacity factor (typically 0.21 to 0.22) while waste-to-energy and run-of-river hydropower have the highest (respectively 0.77 and 0.6). Consequently, for the same amount of output energy (TWh), a higher capacity of solar PV is needed than if waste-to-energy or hydropower were used (MW). Thus, in turn, has direct cost implications, which will be detailed in the following section.

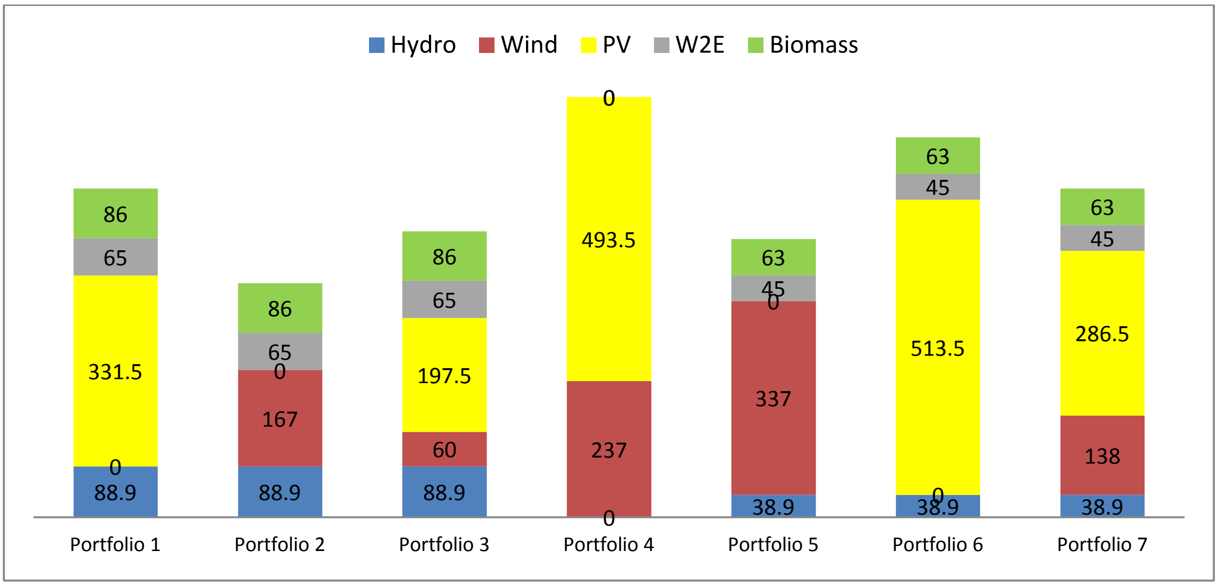


Figure III-1: capacity to be installed in suggested renewable portfolios (MW)

III.2. ECONOMIC ASSESSMENT OF THE PROPOSED PORTFOLIOS

III.2.1. General remarks

As previously mentioned, the proposed portfolios provide only a range of possible snapshots of the Jamaican renewable energy mix in 2030, but do not specify the ramp up trajectories from 2013 through 2030. Many paths could be followed to get to the same result. Time being a crucial factor in investment planning (especially when it comes to renewable energy), this timing uncertainty entail unavoidable costs uncertainties, for two main reasons:

- First, the costs of certain technologies, chiefly wind and solar, and to a lesser extent, waste-to-energy, are expected to drop quite substantially in the near future as a result of increased volume and research efforts. Therefore, the timing of the investment has an important influence on the overall cost of each portfolio.
- Second, as always in investment planning, future costs must be discounted back to the present to reflect the time-value of money. As a result, all things equal, the year in which the investment occurs directly impacts the total cost of the portfolio. The higher the discount rate, the more an economically rational entity will tend to favour the present over the future. In other words, high discount rates might be interpreted as giving a distorted vision of reality as delayed investments always look significantly smaller. All costs presented here have been

discounted back to the present year (2013) using the standard discount rate of 11.95%, as imposed by the OUR for the entire Jamaican electricity sector.

It is assumed that the new capacities will be installed at a steady yearly rate through 2030. As no Network Masterplan nor updated Generation Expansion Plan were available, no detailed year-after-year analysis is planned in the context of this study but rather a simplified approach integrating three time-periods through 2030:

- Short-term: 2013-2015
- Mid-term: 2015-2020
- Long-term: 2020-2030

Importantly, because of both cost and timing uncertainties, and simplifications, the estimates provided here are not intended to provide an accurate picture but rather shed some light on the most meaningful trends and provide general guidance to construct an optimal renewable portfolio taking into account technologies, costs and risks. It should be used as a decision tool when designing and selecting the portfolio to be studied more in depth during the next phase of the project.

III.2.2. Technology and costs assumptions:

The following assumptions have been used regarding the costs of renewable technologies:

US$/kW	Short-term (2013-2015)	Mid-term (2015-2020)	Long-term (2020-2030)
Solar PV	2 689	2 096	1 505
Wind	2 080	1 826	1 699
Hydro	3 500	3 500	3 500
Biomass	3 000	3 000	3 000
Waste-to-Energy	5 900	5 251	5 251

Table III-6: costs of renewable technologies

These numbers are primarily based on a recently series of reports published by IRENA (International Renewable Energy Agency) regarding the costs of renewable energy technologies, except for hydropower.

As far as wind power is concerned, IRENA compares the estimates of cost reduction potential up to 2030 calculated by a range of prominent sources [14]. Average numbers have been calculated by Hinicio for the two periods under scrutiny (2015-2020 and 2020-2030). As for the 2013-2015 period, the average costs of the two wind projects submitted to the OUR in June 2013 by Wigton and Blue Mountain Renewable were calculated and assumed as reference.

Cost reduction potential - Wind (turnkey projects)				
% cost reduction / 2011	2015	2020	2025	2030
IEA				-18,0%
EWEA	-11,0%	-22,0%	-28,0%	-29,0%
GWEC	-5,5%	-10,5%		-17,0%
Mott MacDonald		-12,0%		
US DoE				-10,0%
Average 2015-2020	-12,2%			
Average 2020-2030	-18,3%			

Table III-7: projected variation of wind power costs

As for solar PV, IRENA also compares estimates from the IEA and the European Photovoltaic Industry Association (EPIA) [15]. The average cost per kilowatt of solar PV projects submitted to the OUR in June was calculated and taken as a reference for the 2013-2015 period. The 2015-2020 value assumed in the present study is the average of the OUR value and the 2020 costs provided by the IRENA. Finally, the cost of solar PV for the 2020-2030 period was calculated as the average of the IRENA values for 2020 and 2030.

Cost reduction potential - Solar PV (utility scale) – US$/kW					
	2010	2013	2015	2020	2030
EPIA	3600			1800	1220
IEA	4000			1800	1200
OUR bid		2 689			
Average 2015-2020	2096				
Average 2020-2030	1505				

Table III-8: projected variation of solar power costs

With regard to waste-to-energy technologies, an investment cost of US$5,900/kW is considered for the 2013-2015 period, as estimated recently by the Constant Group in a report to PCJ [6]. A 22% drop in technology cost is assumed by 2020, as envisaged by the IRENA [16] with no further cost decrease after that date. For biomass, the assumption of US$ 3,000 is based on an EU-financed study by Landell Mills Development Consultants published in March 2012 [5].

Finally, the hydropower costs have been provided by the MSTEM.

It is worth noting that all renewable energy cost estimates used in this assessment include average grid connection costs.

III.2.3. Results of financial calculations and recommendations:

Based on the aforementioned set of cost assumptions, the overall investment cost of each portfolio has been calculated.

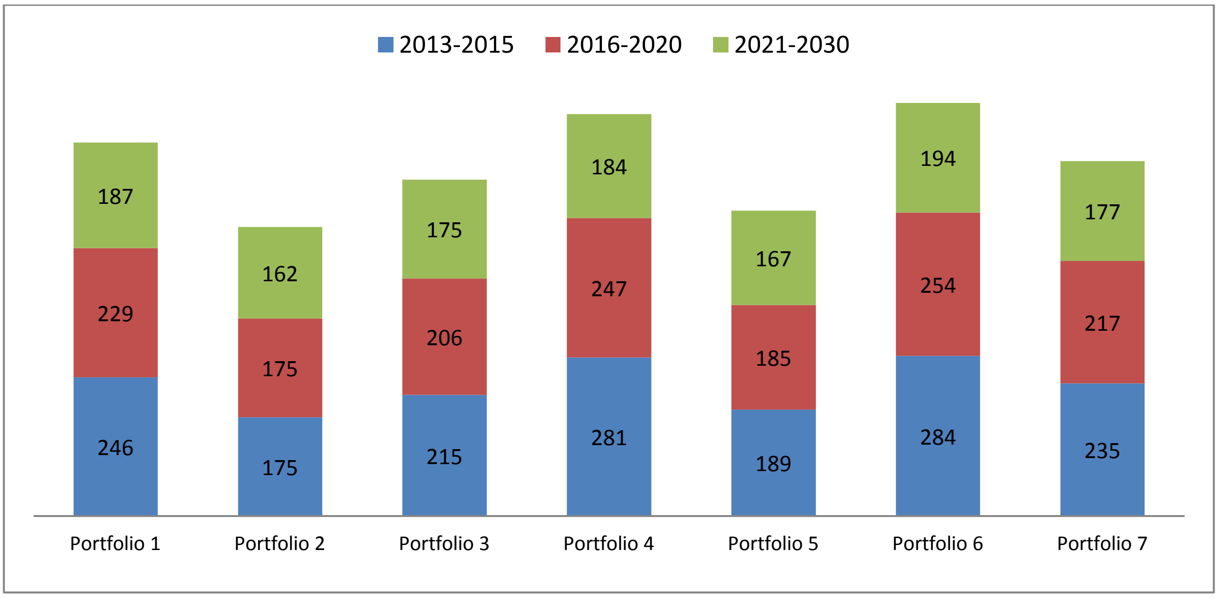


Figure III-2: investment costs for suggested renewable portfolios per period (2013 million USD)

The total investment costs through 2030 associated with each portfolio are as follows (numbers have been rounded up):

	Total investment cost (in 2013 US$)
Portfolio 1 (high base-load / Solar PV)	US$ 660,000,000
Portfolio 2 (high base-load / Wind)	US$ 510,000,000
Portfolio 3 (high base-load / Wind & SolarPV)	US$ 595,000,000
Portfolio 4 (no base-load)	US$ 710,000,000
Portfolio 5 (low base-load / Wind)	US$ 540,000,000
Portfolio 6 (low base-load / Solar PV)	US$ 730,000,000
Portfolio 7 (low base-load / Wind & Solar PV	US$ 630,000,000

Table III-9: total investment costs for suggested renewable portfolios

It must be noted that, at this point in the study, there was no information available about the trajectory to follow in terms of installed capacity and investments. Consequently, in order to avoid any bias between the portfolios, constant investment per year is assumed over the period. This kind of calculations is likely to reduce the apparent cost of a portfolio, but only serves as a comparison basis. The portfolio later selected by the MSTEM is assessed in details later in the document, in chapter VII. Economic Assessment of the Selected Protfolio. Detailed costs of the mentioned chapter should not be compared with the simplified costs presented in the above table.

III.2.4. Discussion and recommendations:

A number of important trends can be highlighted:

- First of all, based on the cost assumptions that have been made, it appears very clearly that solar PV tends to significantly drive up the costs of portfolios. This is illustrated when comparing portfolios 1 and 2 as well as portfolios 5 and 6.
- As far as intermittent renewables are concerned, wind is likely to be more cost-effective than solar PV if Jamaica is to achieve the 30% target, for two main reasons. Firstly, the capacity factors of wind across the island are significantly higher, on average, than those of solar PV. Secondly, installed costs will likely remain lower for wind at least until 2020. The cost of solar PV is expected to drop below that of wind after that date, but because the discount rate is so high, the net effect in total costs is barely visible.
- The technologies and sites with the highest capacity factor should be considered in priority, in order to reduce the amount of required installed power and therefore the overall cost.
- In particular, it is advisable to maximize the amount of base-load power, namely hydro, biomass and waste-to-energy, which combine several advantages on top of a higher capacity factor. By and large, these are conventional technologies already in use at large-scale for years or decades. Additionally, base-load renewables are generally dispatchable (except run-of-river), accurately predictable and therefore easier to manage at the grid level.
- Finally, beyond mere technological and economic factors, more strategic considerations related to the energy diversification strategy of Jamaica should also be carefully examined. While solar PV appears more costly in the short-term, we think it should not be completely ruled out. The diversification of energy sources will increase the resilience of the Jamaican energy system and introducing solar energy, even in small amounts in the short-term, may help mitigate the technology risks associated with the other renewable sources currently envisaged. Moreover, as the wind, hydro, biomass and waste potentials will have to be almost entirely tapped to reach the 2030 target, solar will necessarily have to be the cornerstone of

any further increase in the share of renewables after that date. Therefore, gaining field experience in the short term could be seen as a valuable long-term investment toward a low-carbon electricity system. Lastly, based on the information publicly available, the majority of projects recently submitted to the OUR in the context of the 115MW renewable energy competition, are in fact solar PV projects. Thus solar PV seems to be in the cards in the short-term and we feel it is important to include it into the portfolio to be further analysed in this study.

The following table recapitulates the most important features of the seven portfolios that have been analysed. A traffic-light colour legend has been used to facilitate reading comprehension (good: green; medium: orange; poor: red).

Portfolios	Costs (in 2013 US$ million)	Amount of base-load power	Amount of dispatchable power	Energy diversification
Portfolio 1 (high base-load / Solar PV)	**660**	**42%**	**35%**	**Medium**
Portfolio 2 (high base-load / Wind)	**511**	**59%**	**49%**	**Medium**
Portfolio 3 (high base-load / Wind & SolarPV)	**595**	**48%**	**40%**	**High**
Portfolio 4 (no base-load)	**711**	**0%**	**0%**	**Poor**
Portfolio 5 (low base-load / Wind)	**541**	**30%**	**22%**	**Medium**
Portfolio 6 (low base-load / Solar PV)	**732**	**22%**	**16%**	**Medium**
Portfolio 7 (low base-load / Wind & Solar PV	**630**	**26%**	**19%**	**High**

Table III-10: main features of the suggested portfolios

III.3. PORTFOLIO SELECTED BY THE MSTEM

Based on this assessment, the MSTEM has selected portfolio 3, with little adjustments. An eighth portfolio has been constructed, combining advantages of different scenarios, while being conservative: relatively low cost, large (but realistic) amount of base-load and dispatchable power and high level of energy diversification (all kinds of renewable sources are included).

Regarding biomass, the consultant team opted for a conservative approach, as the development of all six biomass projects appears highly unlikely at this point in time according to the MSTEM. The consultant assumed that the three smallest projects in terms of MW installed, namely Golden Grove, Everglades and Worthy Park, would not be implemented within the time horizon of the study, which seems reasonable as the smallest power plants will likely turn out to be the less profitable and will probably not be developed in the short-to-mid-term. Finally, PV is similar to portfolio #3, wind is slightly higher in order to compensate for the shortfall in biomass power and hydro is used at maximum.

While the consultant was performing the study and after selection of the portfolio by the MSTEM, first results from requests for bids concerning renewables sites were published. The three following bids were successful:

- Wigton Wind Farm: 24 MW Wind (Rose Hill);
- Blue Mountain Renewables: 34 MW Wind at Munroe, St. Elizabeth
- WRB: 20MW Solar at Content Village in Clarendon.

The first of the three bids was already considered as such in the renewable study, since 30 MW wind power were expected at Rose Hill. The successful 24 MW bid can be considered as a first step.
The solar site at Content Village was not selected, but another one close by, connected to the Parnassus substation, was in the portfolio, with 43 MW expected. Considering that connection points are close, impact on the study should be negligible.
The only modification to the base case renewable scenario is the insertion of 34 MW at Munroe, St. Elizabeth, in addition to the 3 MW already existing.

In the mean time, new information was transmitted to the consultant during his final assignment in Jamaica. This information led to significant changes in hydro power potential and the consultant has been requested to perform new simulations to account for these changes. First, the Dry River hydro plant was not a viable option and had to be discarded. Second, the Maggoty Falls plant was to be upgraded in order to double its capacity thanks to the New Maggoty Falls extension. Third, the potential of five (5) hydro run-of-river plants had been re-evaluated. Details can be found in the report "Hydro Power Prefeasibility studies – five (5) selected sites in Jamaica", written by Studio Pietrangeli in October 2013.

The new data selected for these five (5) sites are presented in the following table:

Site	Installed Capacity	Expected energy output
Martha Brae	12.9 MW	36.4 GW.h / year
Rio Cobre	2.0 MW	5.2 GW.h / year
Spanish River	7.7 MW	18.6 GW.h / year
Negro River	2.5 MW	7.5 GW.h / year
Morgan's River	2.7 MW	8.1 GW.h / year

Table III-11: Changes in run-of-river plants in the Corrected and the Alternative Renewable Scenarios

Last but not least, the Mahogany Vale dam is exclusive of the six following run-of-river projects : Spanish River, Negro River, Yallahs River, Green River, Back Rio Grande and Swift River.

All these changes arose after approval of the hypotheses submitted by the consultant to the MSTEM. Consequently it has been decided to keep the original portfolio and create two additional ones:

- a **corrected portfolio** excluding 6 new run-of-river projects and including the other previously mentioned changes.
- an **alternative portfolio** excluding the Mahogany Vale dam and including the other changes.

In order to take these new elements into account while keeping the energy mix unchanged, it was decided to compensate the net changes of renewable energy produced by adjusting the installed capacity at Winchester. The originally selected portfolio along with the corrected and alternative ones are given in full details in the tables below.

Portfolio originally selected by the MSTEM:

Technology	Site	Status	Selected capacity (MW)	Capacity Factor	Annual Energy (GWh)
Wind	Wigton I	existing	20,7	30%	54,4
Wind	Wigton II	existing	18	38%	59,1
Wind	Munro	existing	3	29%	7,5
Wind	Rose Hill	proposed	30	35%	92,0
Wind	Winchester	potential	75	40%	262,8
Hydro	Rio Bueno A	existing	2,5	60%	13,1
Hydro	Maggoty Falls	existing	6,3	60%	33,1
Hydro	Upper White River	existing	3,8	60%	19,9
Hydro	Lower White River	existing	4	60%	21,0
Hydro	Roaring River	existing	3,8	60%	19,9
Hydro	Constant Spring	existing	0,8	60%	4,2
Hydro	Ram's Horn	existing	0,6	60%	3,1
Hydro	Great River	proposed	8	60%	42,0
Hydro	Laughlands	proposed	2	60%	10,5
Hydro	Back Rio Grande	proposed	10	60%	52,5
Hydro	Green River	potential	1,4	60%	7,3
Hydro	Martha Brae	potential	4,8	60%	25,2
Hydro	Rio Cobre	potential	1	60%	5,2
Hydro	Negro River	potential	1	60%	5,2
Hydro	Yallahs River	potential	2,6	60%	13,6
Hydro	Wild Cane River	potential	2,5	60%	13,1
Hydro	Morgan's River	potential	2,3	60%	12,1
Hydro	Spanish River	potential	2,5	60%	13,1
Hydro	Mahogany Vale	potential	50	49%	212,9
Solar	Paradise 1	potential	49,5	22%	93,2
Solar	Paradise 2	potential	30	22%	56,5
Solar	Old Harbour	potential	30	21%	55,7
Solar	Kelly's Pen A	potential	20	22%	38,4
Solar	Micham	potential	25	21%	46,2
Solar	Parnassus	potential	43	21%	80,2
Bio/waste	Appleton	potential	20,5	61%	109,5
Bio/waste	Monymusk	potential	15	52%	68,3
Bio/waste	Frome	potential	27,5	53%	127,7
Bio/waste	Riverton (Kingston)	potential	45	77%	301,6
Bio/waste	Retirement	potential	20	77%	134,0
	Total portfolio	**MW**	**583**	**GWh**	**2120**

Corrected portfolio selected by the MSTEM:

Technology	Site	Status	Selected capacity (MW)	Capacity Factor	Annual Energy (GWh)
Wind	Wigton I	existing	20,7	30%	54,4
Wind	Wigton II	existing	18	38%	59,1
Wind	Munro	existing	37	29%	92,4
Wind	Rose Hill	proposed	30	35%	92,0
Wind	Winchester	potential	55	40%	175,2
Hydro	Rio Bueno A	existing	2,5	60%	13,1
Hydro	Maggoty Falls	existing	12,6	60%	66,1
Hydro	Upper White River	existing	3,8	60%	19,9
Hydro	Lower White River	existing	4	60%	21,0
Hydro	Roaring River	existing	3,8	60%	19,9
Hydro	Constant Spring	existing	0,8	60%	4,2
Hydro	Ram's Horn	existing	0,6	60%	3,1
Hydro	Great River	proposed	8	60%	42,0
Hydro	Laughlands	proposed	2	60%	10,5
Hydro	Back Rio Grande	proposed	10	60%	52,5
Hydro	Martha Brae	potential	12,9	33%	37,3
Hydro	Wild Cane River	potential	2,5	60%	13,1
Hydro	Mahogany Vale	potential	50	49%	212,9
Solar	Paradise 1	potential	49,5	21,50%	93,2
Solar	Paradise 2	potential	30	21,50%	56,5
Solar	Old Harbour	potential	30	21,20%	55,7
Solar	Kelly's Pen A	potential	20	21,90%	38,4
Solar	Micham	potential	25	21,10%	46,2
Solar	Parnassus	potential	43	21,30%	80,2
Bio/waste	Appleton	potential	20,5	61%	109,5
Bio/waste	Monymusk	potential	15	52%	68,3
Bio/waste	Frome	potential	27,5	53%	127,7
Bio/waste	Riverton (Kingston)	potential	45	77%	301,6
Bio/waste	Retirement	potential	20	77%	134,0
	Total portfolio	**MW**	**599**	**GWh**	**2120**

Alternative portfolio selected by the MSTEM:

Technology	Site	Status	Selected capacity (MW)	Capacity Factor	Annual Energy (GWh)
Wind	Wigton I	existing	20,7	30%	54,4
Wind	Wigton II	existing	18	38%	59,1
Wind	Munro	existing	37	29%	92,4
Wind	Rose Hill	proposed	30	35%	92,0
Wind	Winchester	potential	98,5	40%	345,1
Hydro	Rio Bueno A	existing	2,5	60%	13,1
Hydro	Rio Bueno B	existing	1,1	60%	5,8
Hydro	Maggoty Falls	existing	6,3	60%	33,1
Hydro	Upper White River	existing	3,8	60%	19,9
Hydro	Lower White River	existing	4	60%	21,0
Hydro	Roaring River	existing	3,8	60%	19,9
Hydro	Constant Spring	existing	0,8	60%	4,2
Hydro	Ram's Horn	existing	0,6	60%	3,1
Hydro	Great River	proposed	8	60%	42,0
Hydro	Laughlands	proposed	2	60%	10,5
Hydro	Back Rio Grande	proposed	10	60%	52,5
Hydro	Martha Brae	potential	12,9	33%	37,3
Hydro	Rio Cobre	potential	1	60%	5,2
Hydro	Negro River	potential	1	60%	5,2
Hydro	Yallahs River	potential	2,6	60%	13,6
Hydro	Wild Cane River	potential	2,5	60%	13,1
Hydro	Morgan's River	potential	2,3	60%	12,1
Hydro	Spanish River	potential	2,5	60%	13,1
Solar	Paradise 1	potential	49,5	22%	93,2
Solar	Paradise 2	potential	30	22%	56,5
Solar	Old Harbour	potential	30	21%	55,7
Solar	Kelly's Pen A	potential	20	22%	38,4
Solar	Micham	potential	25	21%	46,2
Solar	Parnassus	potential	43	21%	80,2
Bio/waste	Appleton	potential	20,5	61%	109,5
Bio/waste	Monymusk	potential	15	52%	68,3
Bio/waste	Frome	potential	27,5	53%	127,7
Bio/waste	Riverton (Kingston)	potential	45	77%	301,6
Bio/waste	Retirement	potential	20	77%	134,0
	Total portfolio	**MW**	**612**	**GWh**	**2120**

The two following charts show how the new portfolios compare to the other options already analysed, both in terms of installed capacities and overall investment costs. Unsurprisingly, their total installed capacity and cost fall between those of portfolio 2 and portfolio 3.

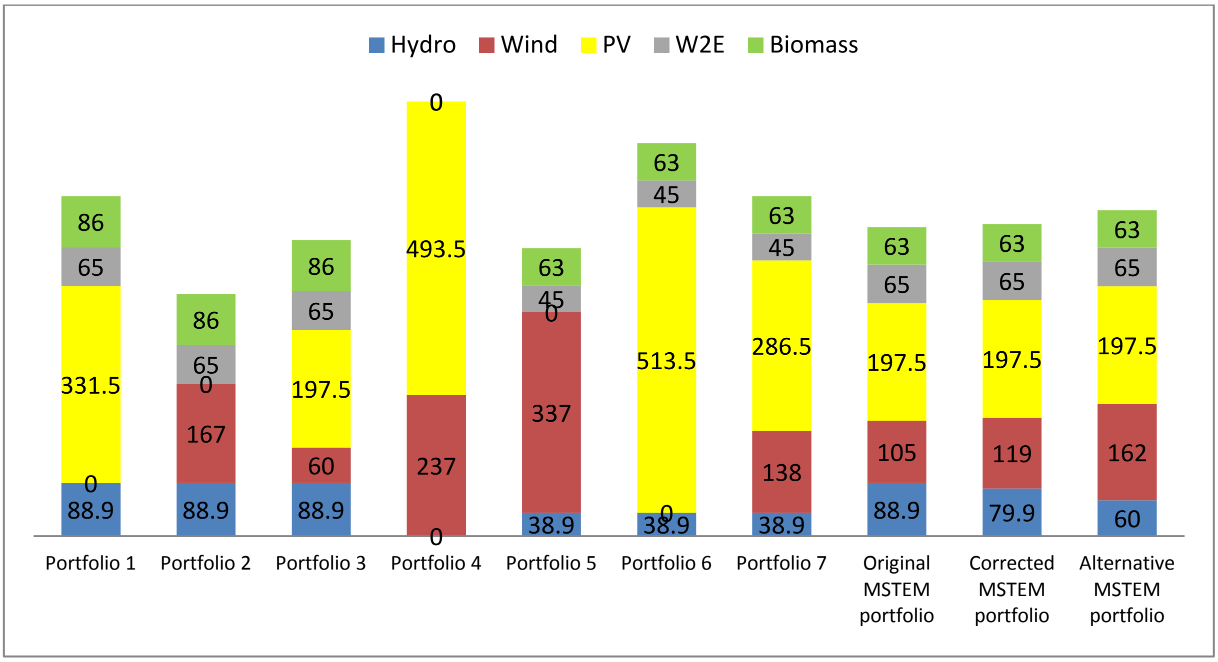


Table III-12: capacity to be installed in suggested renewable portfolios, including MSTEM portfolios (MW)

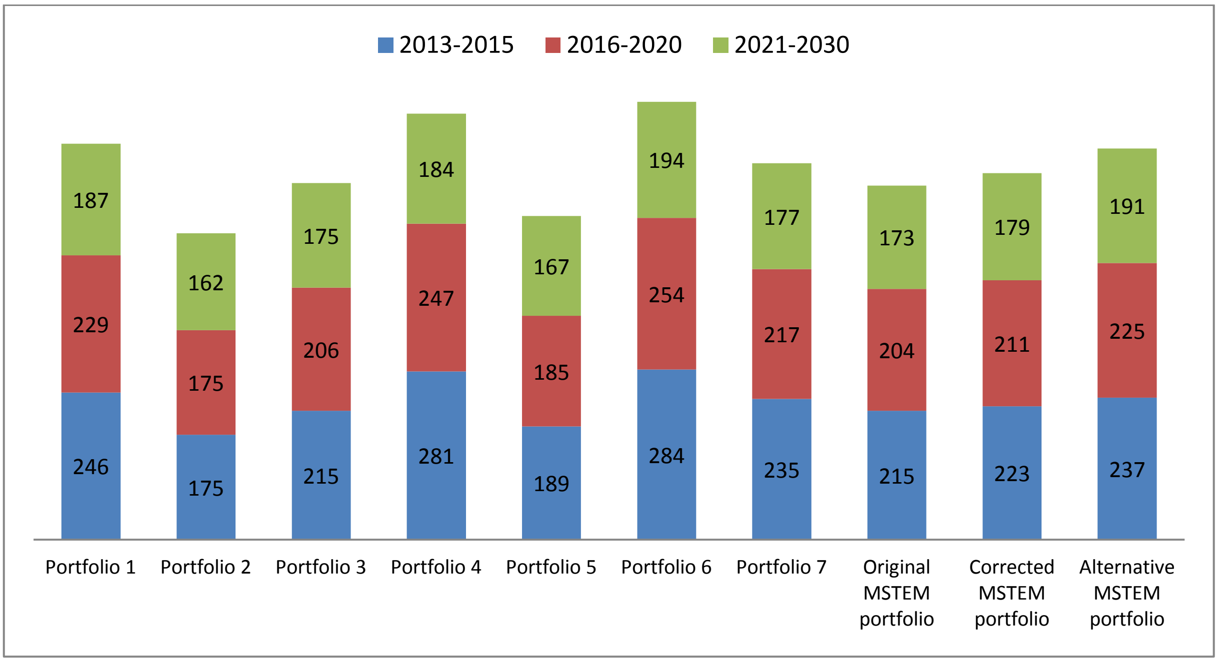


Table III-13: investment costs for suggested renewable portfolios per period, including MSTEM portfolios (2013 million USD)

The total installed capacity in the original MSTEM portfolio is 519.4 MW and the total investment cost through 2030 is around US$ 592 million (in 2013 US$).

The total installed capacity in the corrected MSTEM portfolio is 524.4 MW and the total investment cost through 2030 is around US$ 613 million (in 2013 US$).

The total installed capacity in the original MSTEM portfolio is 547.5 MW and the total investment cost through 2030 is around US$ 654 million (in 2013 US$).

As explained in section III.2.3, these calculations are rough calculations to be compared with previously presented portfolios and consider constant investment per year over the period.

IV. THE JAMAICA ELECTRICITY NETWORK IN 2030

IV.1. 2030 GRID MODEL

IV.1.1. Load

The annual growth rate of the electricity demand from 2013 to 2030 has been assumed to be 2.5%.

This study also assumes that the increase in demand will be equally distributed among the loads represented in the 2013 network. Thus, with this growth rate, given that a peak load of 703 MW has been assumed for 2013, the demand will peak at 1063.7 MW in 2030. The power factors of the loads in 2013 are kept unchanged to represent the load in 2030.

As a consequence, the following table gives the new values of the load in 2030:

Bus Name	Voltage	PSSE Bus	Pload MW)	Qload (Mvar)
TREDEGAR	69 kV	5	41.169	13.454
HOPE	69 kV	16	37.318	12.195
MILCHELT	69 kV	17	25.601	8.367
PARADISE	69 kV	24	31.446	10.277
BLEDGE	69 kV	26	2.313	0.756
CANE RIV	69 kV	27	14.408	4.708
HIGHGATE	69 kV	29	9.331	3.049
QUEENS D	69 kV	30	39.031	12.755
OCHO	69 kV	32	20.910	6.833
BOGUE_69	69 kV	33	67.020	21.903
ROSE HAL	69 kV	35	17.182	5.615
OBAY69	69 kV	39	32.852	10.736
DUNCANS6	69 kV	40	10.309	3.369
3MLS69	69 kV	45	30.299	9.901
WBLVD69	69 kV	46	65.230	21.317
PORT ANT	69 kV	48	15.012	4.906
GREENWOO	69 kV	60	12.692	4.148
LYSSONS	69 kV	61	9.151	2.990
PORUS	69 kV	62	15.829	5.173
R RIVER	69 kV	66	20.075	6.560
MARTHA B	69 kV	67	6.782	2.217
WKH69	69 kV	69	32.268	10.546
PNASUS69	69 kV	70	20.399	6.666
ANNOTTO	69 kV	71	6.508	2.127
UW RIVER	69 kV	74	5.081	1.660
KNDAL 69	69 kV	75	31.377	10.254
MONYMUSK	69 kV	78	12.704	4.151
OROCABES	69 kV	79	11.242	3.673
MAGGOTTY	69 kV	80	27.380	8.948

UP PARK	69 kV	82	22.499	7.352
TWICKENH	69 kV	85	38.372	12.541
MAY PEN	69 kV	88	20.703	6.766
GROAD_69	69 kV	90	36.362	11.884
CSPRING	69 kV	91	39.270	12.833
S_ TREE6	69 kV	92	40.163	13.125
NAGGOS H	69 kV	94	29.355	9.594
GOODYEAR	69 kV	99	14.306	4.676
HBAY_69	69 kV	101	51.257	16.751
RFORT69	69 kV	102	23.806	7.780
RHODEN P	69 kV	105	23.749	7.762
DUHANEY6	69 kV	107	32.353	10.573
CARDIFF	69 kV	109	26.589	8.690
JAM13.8	*13.8 kV*	*113*	*0*	*42.619*
TOTAL			**1069.7 MW**	**392.2 MVAr**
			= 703 x $(1+2,5\%)^{2030-2013}$	= 257.8 x $(1+2,5\%)^{2030-2013}$

Table IV-1: Load data - 2030 Jamaican transmission grid

The situation of the **last load**, situated at **Halse Hall,** is very specific. It appears to be linked to the co-generation facility of JAMALCO. However, according to [1], the power outputs of both the Halse Hall and the Spring Village co-generation facilities are not guaranteed. Without more information, and considering the low influence of these plants on the network (about 6 MW), in order to be realistic it was decided to consider these co-generation plants as disconnected. However, for the Halse Hall load, it would not have been possible to keep it since the 42 MVAr would normally have been delivered by the co-generation plants, since they can produce up to 3x13.5 = 40.5 MVAr. For this reason, the associated load was also considered disconnected.

According to last available information, there is a project of generation extension at Jamalco. This confirms that the load will be fully supplied by the local generation and will have no impact on the grid. Possible extra power could be supplied to the grid. In this case, it would have to compete in merit order against all other power plant, including renewables. Should this generation be competitive, it would come in replacement of other conventional plants such as the units in Old Harbour. In these circumstances, it is not likely that such a project would create additional constraints in loadings or voltages.

IV.1.2. Clarification about run-of-river plant

As evocated in chapter II.2.2 Methodology, different seasons were differentiated in the model of the Jamaica grid. More specifically, document [4] aimed at studying the feasibility of the Mahogany dam. However, it contains relevant data about flows of water in both Yallahs basin and Northern Blue Mountain basin.

According to the document a factor 7 should be chosen for the ratio of water flow during high rain season and low rain season in the Yallahs basin. This ratio should be chosen equal to 5.3 for the Northern Blue Mountain basin. An intermediate value of 6.15 was then chosen for the rest of the run-of-river hydraulic generation plants.

This study indicated that choosing November and December for the high flow period and choosing July and August for the low flow period would be relevant. The rest of the year was then considered as intermediate flow period, with an output calculated in order to satisfy the energy production over the entire year.

The following table clarifies this simulation choice:

Name	Hydro area	High/Low ratio	Capacity (MW)	P_High (MW)	P_Med (MW)	P_Low (MW)	Annual energy output (GWh)
Rio Bueno A	Other	6,15	2,5	2,500	1,525	0,407	13,12
Maggoty Falls	Other	6,15	6,3	6,300	3,842	1,024	33,06
Upper White River	Other	6,15	3,8	3,800	2,317	0,618	19,94
Lower White River	Other	6,15	4	4,000	2,440	0,650	20,99
Roaring River	Other	6,15	3,8	3,800	2,317	0,618	19,94
Constant Spring	Blue Mountain	5,3	0,8	0,800	0,483	0,151	4,2
Ram's Horn	Blue Mountain	5,3	0,6	0,600	0,362	0,113	3,15
Great River	Other	6,15	8	8,000	4,878	1,301	41,98
Laughlands	Other	6,15	2	2,000	1,219	0,325	10,49
Back Rio Grande	Blue Mountain	5,3	10	10,000	6,030	1,890	52,47
Green River	Other	6,15	1,4	1,400	0,854	0,228	7,35
Martha Brae	Other	6,15	4,8	4,800	2,927	0,781	25,19
Rio Cobre	Other	6,15	1	1,000	0,610	0,160	5,25
Dry River	Blue Mountain	5,3	0,8	0,800	0,483	0,151	4,2
Negro River	Yallahs Bassin	7	1	1,000	0,615	0,143	5,25
Yallahs River	Yallahs Bassin	7	2,6	2,600	1,598	0,371	13,64
Wild Cane River	Yallahs Bassin	7	2,5	2,500	1,537	0,357	13,12
Morgan's River	Yallahs Bassin	7	2,3	2,300	1,414	0,330	12,07
Spanish River	Blue Mountain	5,3	2,5	2,500	1,537	0,357	13,12

Table IV-2: Capacity of run-of-river plants according to seasons

In the above table, the plants in blue already exist and will thus be considered in both the 2030 Conventional Plants scenario and the 2030 with Renewable scenario.

IV.1.3. Adjustment of the Maggoty Falls transformer

The Maggoty Falls run-of-river hydro plant (bus 25) represents a problem: its step-up transformer has a very high ratio of 1.05, and is supposed to be not adjustable.

As a consequence, in low and intermediate flow situations, where the power generated by the run-of-river plant is quite low, the voltage at this bus will be very low: there will be almost no voltage drop from this bus to the 69kV bus, so its voltage will be driven by the voltage of the 69kV bus. If the 69kV bus is at 1 p.u., the Maggoty Falls plant will thereby be at approximately at 0.95p.u., which is already close to the 0.94p.u. limit.

Since the area surrounding this bus is heavily loaded (the Maggoty bus and even the Paradise bus are), the voltage of the area will tend to be lower than the rest of the network. And so will the Maggoty Falls plant bus be even lower, causing a surge in voltage constraints.

To cope with this issue, it has been decided to change its ratio from 1.05 to 1. This allows the results to be more representative.

IV.1.4. Correction of Bogue GT step up transformers

As mentioned previously, it appeared that some step-up transformers – namely those related to the Bogue GT6, GT7, GT8 and GT9 units – were inaccurately modelled. Their reactances were supposedly of 0.98 per unit, as declared in the inception report. The consultant has no doubt this must be a data collection error, since no transformer would have such important reactance.

Indeed, such a reactance would consume, on three phases, a reactive power Q:

$$Q(VAr) = 3.X(\Omega).I(A)^2 = 3.X(pu).\frac{Un(V)^2}{Sn(VA)}.\left(\frac{S(VA)}{\sqrt{3}.U(V)}\right)^2 = X(pu).S(VA)$$

For instance, with such a reactance, if the GT7 was producing its maximum output of 14 MW and 14 MVAr (19.8 MVA), its transformer would then be consuming 19.4 MVAr.

Since a typical value for a transformer reactance is in the order of magnitude of 0.1 pu, it is very likely that a zero is missing in the reactances of these transformers. That is why their value has been changed to 0.098 p.u.

IV.2. THE 2030 CONVENTIONAL PLANTS SCENARIO

IV.2.1. Evolution of generation

This scenario relies on the document [1] and is intended to offer a reference point with which the 2030 with Renewable scenario could be compared.

Document [1] gives a clear plan about which plants should be decommissioned and when. It also describes which conventional plants should be built to satisfy the growing demand and loss of generation induced by the decommissioning of the oldest plants. It does so in order to minimize the generation costs.

However, in document [1] the network is not considered, and neither are the locations of these new plants. What's more, this document considers an average load growth rate close to 4%, which is very different from the 2.5% growth rate chosen in this study. Thus, the consultant has adapted the generation plan in order to cope with this change. Finally, in order to minimize the impact of these new plants and thus optimize the functioning of the system, some choices have been made by the consultant, with validation by the client. All these elements lead to the following Conventional Expansion plan.

With the 2.5% load growth rate hypothesis, considering a peak load of 703 MW in 2013, this peak will reach 1069.7 MW in 2030. This means an additional 366.7 MW capacity will be required to cover the increasing load.

What's more, document [1] states that the following decommissionings will take place (net capacity given in parenthesis):

- In 2014, a total of 249 MW:
  - **OH2** (57 MW) + **OH3** (61.8 MW) + **OH4** (65.1 MW) at **Old Harbour**
  - **B6** (65.1 MW) at **Hunts bay**
- In 2018, a total of 60 MW:
  - **JPPC** (30 MW) and **JPPC2** (30 MW) at **Rockfort**
- In 2020, a total of 38.4 MW:
  - **RF1** (19.2 MW) and **RF2** (19.2 MW) at **Rockfort**
- In 2026, a total of 124.3 MW:
  - The 2 barges of the JEP complex at **Old Harbour**, referenced as **JEP1** (4x12.06 MW) and **JEP2** (4x12.06 MW) and **NEW JEP** (3x17.08 MW)

Altogether, this means a loss of 471.4 MW of generating capacity. The Jamaican network will then need a total of 366.7 + 471.4 = 838.4 MW of generating capacity to be built by 2030. The consultant proposes to follow document [1], in its optimal scenario, to the point where the 838.4 MW required are built:

- In 2014, 3 NGCC units would be connected (**+351 MW**)
- In 2016, a coal unit would be connected (**+114 MW**)
- In 2017, a GT unit would be connected (**+39 MW**)
- In 2018, a coal unit would be connected (**+114 MW**)
- In 2020, a coal unit would be connected (**+114 MW**)
- In 2026, a coal unit would be connected (**+114 MW**)

The commissioning of these plants would add 846 MW to the generation capability, covering the 838 MW required.

IV.2.2. Location of new power plants

As explained previously, an important information lacking consists in the location of the new power plants. Since many power plants are expected to be decommissioned by 2030, a simple choice is to put new power plants in locations where today those soon-to-be-decommissioned plants exist.

More specifically:

- Since Old Harbour will lose 309.2 MW generating capacity, connecting the 3 NGCC units of 2014 (351 MW new capacity) at this location would be reasonable.
- Since Hunts bay will lose 65 MW generating capacity, the coal unit of 2016 (114 MW) could be connected there.
- Since Rockfort will lose 98.4 MW generating capacity, the coal unit of 2018 (114 MW) could be connected there.

With these assumptions, one GT unit (39 MW) and two coal unit (114 MW each) are still to be placed.

- The GT unit of 2017 (39 MW) could also be connected at Hunts bay.
- Given its central location and highly meshed situation, Old Harbour should be able to accommodate the coal unit of 2020 (114 MW).

- Last, the coal unit of 2026 could be built at Duncan. Simulations have been ran and concluded that neither Rockfort nor Bogue would be able to accommodate such a surge of generating capability.

The last question concerned the location of the coal unit of 2026 (114 MW). For this specific point, the consultant ran the probabilistic approach to consider the impact of different locations. The results are presented in appendix 3.

The main results are given bellow:

- Rockfort is not suitable, especially in Low Flow situations, because the load flows coming from Rockfort would generate high voltage drops and/or overload the surrounding lines.
- Bogue would be a legitimate candidate, both because the surrounding network is well meshed and because the existing units are GT units and as such are peak-load units.
- Duncan is an even better candidate, as it occupies a strategic location on the network and would help maintain the voltage of its surrounding area (by comparison, the voltage at Bogue is already very well supported by the numerous units already existing).

As a consequence, it was decided to implement this coal unit at Duncan.

To summarize the previous choices, the evolution of the Jamaican network would be the following:

- The 3 NGCC units of 2014 would be connected at **Old Harbour** (**+351 MW**)
- The coal unit of 2016 would be connected at **Hunts bay** (**+114 MW**)
- The GT unit of 2017 would be connected at **Hunts bay** too (**+39 MW**)
- The coal unit of 2018 would be connected at **Rockfort** (**+114 MW**)
- The coal unit of 2020 would be connected at **Old Harbour** (**+114 MW**)
- The coal unit of 2026 would be connected at **Duncan** (**+114 MW**)

IV.2.3. New step-up transformers

As stated in the general methodology of this study, the first step of the 2030 study is to analyze the constraints that will arise on the network if no reinforcements are implemented.

However, considering that new generators will be built by then, new transformers have to be specified in order to connect them to the grid.

In the simulation model, the following transformers had to be implemented:

New Sites	From bus	To bus	From bus Voltage	To bus Voltage	Generator SMax (MVA)	Transformer rating (MVA)
Old Harbour (GCC)	41		13.8 kV		143	160
Old Harbour (GCC)	47	114	13.8 kV	138 kV	143	160
Old Harbour (GCC)	50		13.8 kV		143	160
Hunts bay (Coal)	57	101	13.8 kV	69 kV	139	160
Hunts bay (Gas Turbine)	15		11.5 kV	69 kV	47	60
Rockfort (Coal)	37	102	13.8 kV	69 kV	139	160
Duncan (Coal)	42	33	13.8 kV	69 kV	139	160
Old Harbour (Coal)	52	114	13.8 kV	138 kV	139	160

Table IV-3: List of new step-up transformers required

The Huns bay 39 MW Gas Turbine is very close in power flows to each of the 38 MW units of the Gas Combined Cycle located at Bogue (totalizing 114 MW). What's more, in both cases, the transformers are **60 MVA, 13.8 kV/69 KV transformers**. For this reason, the Hunts bay 39 MW Gas Turbine transformer has been chosen as an exact copy of the Bogue 38 MW Gas Combined Cycle transformers.

Considering the new Hunts bay, Rockfort and Duncan 114 MW plants, they would need appropriate **160 MVA 13.8 kV / 69 kV transformers**. No existing step up transformer on the 2013 network can be used as such. For this reason, the electrical characteristics of the biggest existing step up transformer were chosen (the step up transformer of the former B6 68.5 MW plant, which is a 80 MVA 13.8 kV/69 kV transformer) and re-scaled to 160 MVA. By doing so, the per unit values of this transformer remain intact.

Finally, as far as the 3 Old Harbour GCC and the Old Harbour coal plants are concerned, the same electrical characteristics were chosen but with appropriate transformer ratios, since the Winding 2 Nominal voltage are 138 kV instead of 69 kV.

IV.2.4. Full description of the generation portfolio

Considering the elements above, the 2030 Conventional Scenario will then be the following:

Technology	**Site name** (PSSE Bus)	**PMax (MW)**	**QMax (MVAr)**				
Gas Combined Cycle	Bogue (23, 76, 77)	114	66				
Combustion Turbine	Bogue (10, 11, 43, 56, 58, 63)	103.5	111				
Combustion Turbine	Huntsbay (12, 13)	54	25				
Medium Speed Diesel	Huntsbay (300, 301)	60	30				
Gas Combined Cycle	Old Harbour (41, 47, 50)	3x117 = 351	3x82 = 246				
Coal	Huntsbay (57)	114	80				
Gas Turbine	Huntsbay (15)	39	27				
Coal	Rockfort (37)	114	80				
Coal	Duncan (42)	114	80				
Coal	Old Harbour (52)	114	80				
Wind	Wington I & II (202)	38.7	0				
Wind	Munro I (503)	3	0				
		High Flow		**Intermediate Flow**		**Low Flow**	
		PGen (MW)	**QMax (MVAr)**	**PGen (MW)**	**QMax (MVAr)**	**PGen (MW)**	**QMax (MVAr)**
Hydro run-of-river	Rio Bueno (65)	2.5	1	1.52	0.61	0.41	0.16
Hydro run-of-river	Maggoty Falls (25)	6.3	2.52	3.84	1.54	1.02	0.41
Hydro run-of-river	Upper White River (64)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Lower White River (68)	4	1.6	2.44	0.98	0.65	0.26
Hydro run-of-river	Roaring River (59)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Constant Spring (91)	0.8	0.32	0.48	0.19	0.15	0.06
Hydro run-of-river	Ram's Horn (711)	0.6	0.24	0.36	0.14	0.11	0.04

Table IV-4: Generation portfolio of the 2030 Conventional Plants scenario

Remarks:

- P_{max} of GT8 (PSSE bus 58) situated at Bogue, has been set to 14 MW instead of the 18 MW of the inception report, in accordance with the value given to the consultant in the PSSE file.

- According to the Generation Expansion Plan, Pmax at the six combustion turbines plant of Bogue should be 115.5 MW instead of 103.5 MW. The difference is possibly explained by a choice of the operator to guarantee a power reserve.

- According to the Generation Expansion Plan, Pmax at the six medium speed diesel generators plant of Hunts bay should be 65.5 MW instead of 60 MW. Again, the difference might be explained by a choice of the operator to guarantee a power reserve.

- For the new units, QMax has been chosen in order to have tan(φ) = 0.7 when reaching (P_{max}, Q_{max}). In other words, the alternators have a S_{max} such that $S_{max} = 1.2*P_{max}$. The same law will apply for waste and co-generation power plants in the 2030 With Renewable scenario.

- For the run-of-river plants, as specified in the previous report, a tan(φ) = 0.4 when reaching (P_{max}, Q_{max}) has been chosen.

IV.3. THE 2030 WITH RENEWABLE PORTFOLIO

IV.3.1. Renewable portfolio

As requested, the renewable portfolio selected by the MSTEM (see section 3) has been implemented.

As explained in the previous chapter of this document, two additional version of the portfolio have been created to account for new information available on hydropower development and first results of the call for bids launched by the MSTEM for renewable energy.

As a reminder, these bids are as follow:

- Wigton Wind Farm: 24 MW Wind (Rose Hill); Site 6
- WRB: 20MW Solar at Content Village in Clarendon; Site 7
- Blue Mountain Renewables: 34 MW Wind at Munroe, St. Elizabeth

The first of the three bids was already considered as such in the renewable study, since 30 MW wind power were expected at Rose Hill. The solar site at Content Village was not selected, but another one close by, connected to the Parnassus substation, was in the portfolio, with 43 MW expected. Considering that connection points are close, impact on the study should be negligible. The only modification to the base case renewable scenario is the insertion of 34 MW at Munroe, St. Elizabeth, in addition to the 3 MW already existing.

The resulting portfolio showed both a changes in the renewable share in electricity generation in 2030. In order to cope with the issue, the consultant decided to adjust installed capacity in Winchester accordingly. Winchester is used as the fitting variable for various reasons. First, it is the largest renewable unit in Jamaica in 2030; second biomass/waste was already specifically reduced by the MSTEM; then hydropower have been clearly defined and cannot be adjusted anymore and finally because solar power is already very high in capacity, but still does not represent much of the electricity generated.

In the corrected scenario, Winchester has been decreased to 55MW and in the alternative scenario, it has been increased to 98.5MW.

IV.3.2. Adjustment of the conventional plants

The 2030 With Renewable portfolio assumes an ambitious objective of renewable penetration rate. No less than 500 MW installed capacity of renewable energy are added to the system.

It would not be realistic to simply add this new capacity to the 2030 Conventional Plants scenario, as some of these new conventional plants would become irrelevant with the commissioning of these renewable energy sources.

However, it would be equally unwise to consider these 500 MW of renewable as the same conventional capacity, because of its intermittent nature. For instance, 40 MW are composed of run-of-river plants, the output of which dramatically drops in low flow periods, and 200 MW are made of photovoltaic plants, which cannot be expected to generate power at night.

To cope with these considerations, the 2030 With Renewable scenario was constructed in two steps: first, starting from the 2030 Conventional Plants scenario, the renewable portfolio chosen was added. Then, conventional generation was taken out, for a total of 288 MW:

- The GT 5 unit (21.5 MW)(PSSE bus 13) was considered decommissioned because of its great age and expansive price.
- Three plants of the generation plan – namely the Duncan coal unit of 2026 (114 MW), the Old Harbour coal unit of 2020 (114 MW) and the Hunts bay GT unit of 2017 (39 MW) – were considered never built.

As well, the old cogeneration (Halse Hall and Spring Village) were also retired. These adjustments are made based on support to the grid provided by the units, measured by the consultant through its simulations, and commissioning dates. It would not be realistic for example to delete the CCGT planned to be commissioned in Old Harbour in 2014 and to keep the coal unit planned to be commissioned at the same location in 2026.

IV.3.3. Full description of the original generation portfolio

Technology	Site name (PSSE Bus)	PMax (MW)	QMax (MVAr)
Gas Combined Cycle	Bogue (23, 76, 77)	114	66
Combustion Turbine	Bogue (10, 11, 43, 56, 58, 63)	103.5	111
Combustion Turbine	Huntsbay (12)	32	15
Medium Speed Diesel	Huntsbay (300, 301)	60	30
Gas Combined Cycle	Old Harbour (41, 47, 50)	3x117 = 351	3x82 = 246
Coal	Huntsbay (57)	114	80
Coal	Rockfort (37)	114	80
Waste	Riverton (601)	45	31.5
Waste	Retirement (602)	20	14
Photovoltaic	Paradise 1 (401)	49.5	0
Photovoltaic	Paradise 2 (402)	30	0
Photovoltaic	Old Harbour (114)	30	0
Photovoltaic	Kelly's Pen A (403)	20	0
Photovoltaic	Micham (409)	25	0
Photovoltaic	Parnassus (411)	43	0
Wind 1	Wington I & II (202)	38.7	0
Wind 1	Rose Hill (500)	30	0
Wind 1	Munro I (503)	3	0
Wind 2	Winchester (502)	75	0
Co-generation	Appleton (604)	20.5	14.3
Co-generation	Monymusk (78)	15	10.5
Co-generation	Frome (606)	27.5	19.2
Dam	Magohany Vale (710)	50	35

		High Flow		Intermediate Flow		Low Flow	
		PGen (MW)	QMax (MVAr)	PGen (MW)	QMax (MVAr)	PGen (MW)	QMax (MVAr)
Hydro run-of-river	Rio Bueno (65)	2.5	1	1.52	0.61	0.41	0.16
Hydro run-of-river	Maggoty Falls (25)	6.3	2.52	3.84	1.54	1.02	0.41
Hydro run-of-river	Upper White River (64)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Lower White River (68)	4	1.6	2.44	0.98	0.65	0.26
Hydro run-of-river	Roaring River (59)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Constant Spring (91)	0.8	0.32	0.48	0.19	0.15	0.06
Hydro run-of-river	Ram's Horn (711)	0.6	0.24	0.36	0.14	0.11	0.04
Hydro run-of-river	Great River (115)	8	3.2	4.88	1.95	1.3	0.52
Hydro run-of-river	Laughlands (701)	2	0.8	1.22	0.49	0.32	0.13
Hydro run-of-river	Back Rio Grande (700)	10	4	6.03	2.41	1.89	0.76
Hydro run-of-river	Green River (702)	1.4	0.56	0.85	0.34	0.23	0.09
Hydro run-of-river	Martha Brae (67)	4.8	1.92	2.93	1.17	0.78	0.31
Hydro run-of-river	Rio Cobre (703)	1	0.4	0.61	0.24	0.16	0.06
Hydro run-of-river	Dry River (704)	0.8	0.32	0.48	0.19	0.15	0.06
Hydro run-of-river	Negro River (705)	1	0.4	0.61	0.25	0.14	0.06
Hydro run-of-river	Yallahs River (706)	2.6	1.04	1.6	0.64	0.37	0.15
Hydro run-of-river	Wild Cane River (707)	2.5	1	1.54	0.61	0.36	0.14
Hydro run-of-river	Morgan's River (708)	2.3	0.92	1.41	0.57	0.33	0.13
Hydro run-of-river	Spanish River (709)	2.5	1	1.54	0.61	0.36	0.14

Table IV-5: Generation portfolio of the 2030 With Renewable scenario

IV.3.4. Full description of the corrected generation portfolio

Technology	**Site name** (PSSE Bus)	**PMax (MW)**	**QMax (MVAr)**				
Gas Combined Cycle	Bogue (23, 76, 77)	114	66				
Combustion Turbine	Bogue (10, 11, 43, 56, 58, 63)	103.5	111				
Combustion Turbine	Huntsbay (12)	32	15				
Medium Speed Diesel	Huntsbay (300, 301)	60	30				
Gas Combined Cycle	Old Harbour (41, 47, 50)	3x117 = 351	3x82 = 246				
Coal	Huntsbay (57)	114	80				
Coal	Rockfort (37)	114	80				
Waste	Riverton (601)	45	31.5				
Waste	Retirement (602)	20	14				
Photovoltaic	Paradise 1 (401)	49.5	0				
Photovoltaic	Paradise 2 (402)	30	0				
Photovoltaic	Old Harbour (114)	30	0				
Photovoltaic	Kelly's Pen A (403)	20	0				
Photovoltaic	Micham (409)	25	0				
Photovoltaic	Parnassus (411)	43	0				
Wind 1	Wington I & II (202)	38.7	0				
Wind 1	Rose Hill (500)	30	0				
Wind 1	Munro I (503)	3	0				
Wind 1	Munro II (503)	34	0				
Wind 2	**Winchester (502)**	**55**	**0**				
Co-generation	Appleton (604)	20.5	14.3				
Co-generation	Monymusk (78)	15	10.5				
Co-generation	Frome (606)	27.5	19.2				
Dam	**Magohany Vale (710)**	**50**	**35**				
		High Flow		**Intermediate Flow**		**Low Flow**	
		PGen (MW)	**QMax (MVAr)**	**PGen (MW)**	**QMax (MVAr)**	**PGen (MW)**	**QMax (MVAr)**
Hydro run-of-river	Rio Bueno (65)	2.5	1	1.52	0.61	0.41	0.16
Hydro run-of-river	Maggoty Falls (25)	12.6	5.04	7.68	3.08	2.04	0.82
Hydro run-of-river	Upper White River (64)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Lower White River (68)	4	1.6	2.44	0.98	0.65	0.26
Hydro run-of-river	Roaring River (59)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Constant Spring (91)	0.8	0.32	0.48	0.19	0.15	0.06
Hydro run-of-river	Ram's Horn (711)	0.6	0.24	0.36	0.14	0.11	0.04
Hydro run-of-river	Great River (115)	8	3.2	4.88	1.95	1.3	0.52
Hydro run-of-river	Laughlands (701)	2	0.8	1.22	0.49	0.32	0.13
Hydro run-of-river	**Back Rio Grande (700)**	**-**	**-**	**-**	**-**	**-**	**-**
Hydro run-of-river	**Green River (702)**	**-**	**-**	**-**	**-**	**-**	**-**
Hydro run-of-river	Martha Brae (67)	12.90	5.16	2.62	1.05	1.55	0.62
Hydro run-of-river	Rio Cobre (703)	2.00	0.80	0.34	0.14	0.20	0.08
Hydro run-of-river	**Dry River (704)**	-	-	-	-	-	-
Hydro run-of-river	**Negro River (705)**	-	-	-	-	-	-
Hydro run-of-river	**Yallahs River (706)**	-	-	-	-	-	-
Hydro run-of-river	Wild Cane River (707)	2.50	1.00	1.54	0.61	0.36	0.14
Hydro run-of-river	Morgan's River (708)	2.70	1.08	0.64	0.26	0.27	0.11
Hydro run-of-river	**Spanish River (709)**	**-**	**-**	**-**	**-**	**-**	**-**

Table IV-6: Corrected Generation portfolio of the 2030 With Renewable scenario

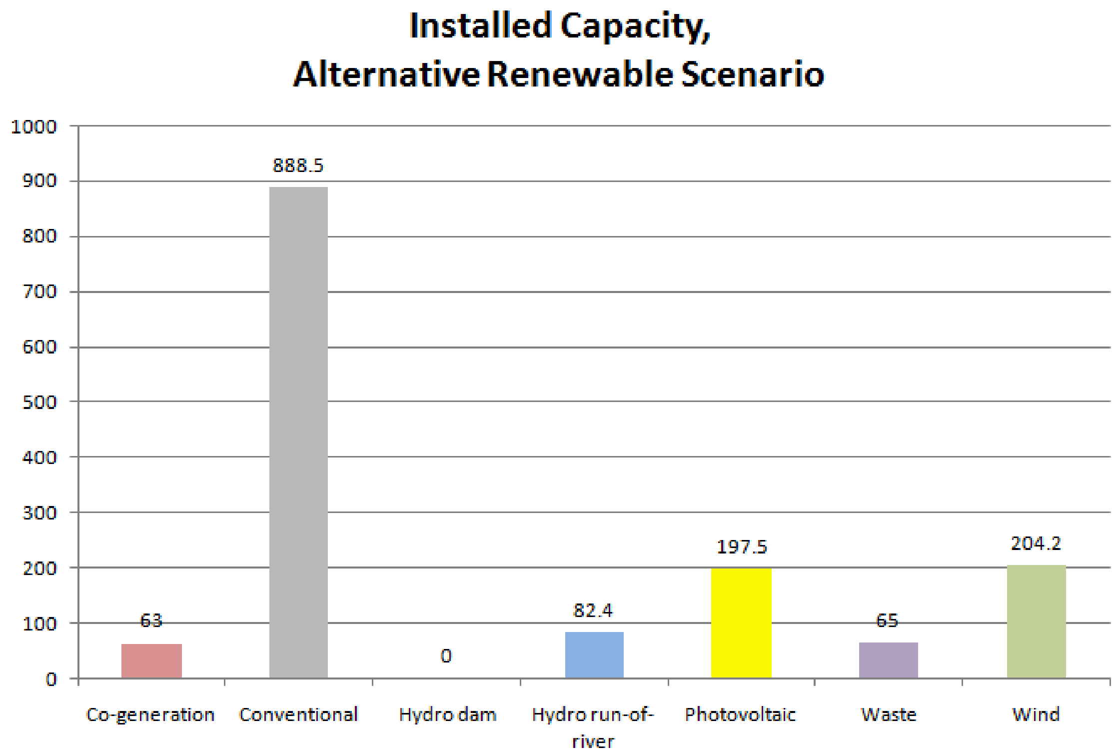
IV.3.5. Full description of the alternative generation portfolio

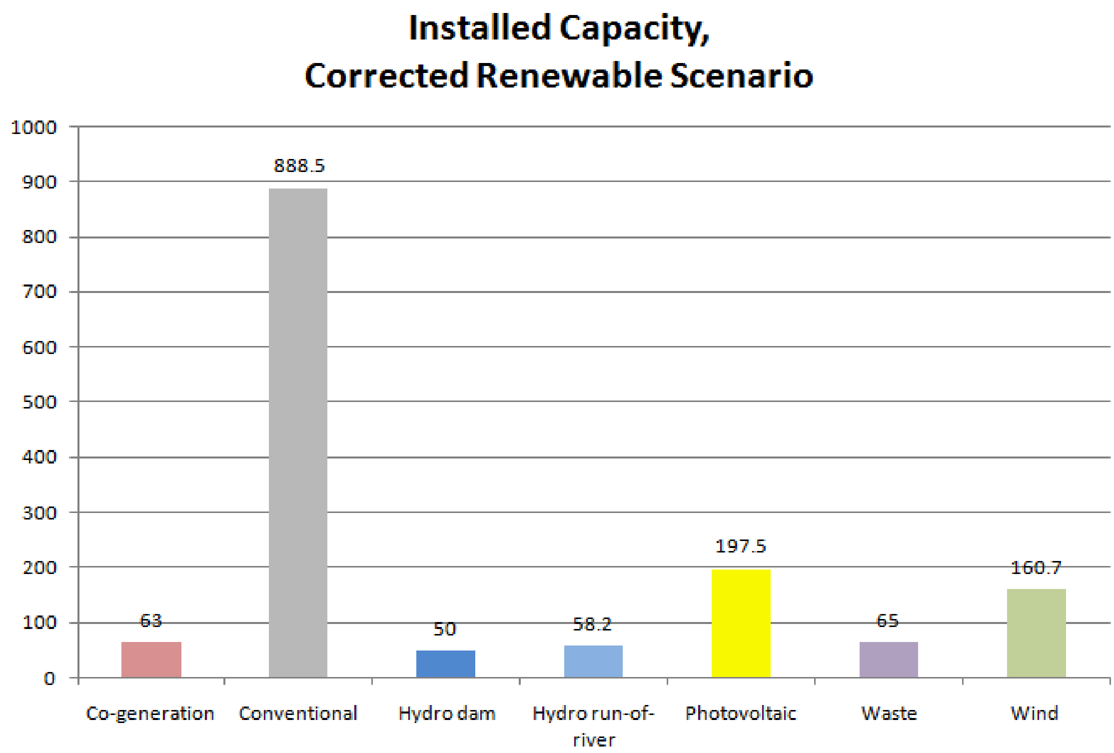
Technology	Site name (PSSE Bus)	PMax (MW)	QMax (MVAr)
Gas Combined Cycle	Bogue (23, 76, 77)	114	66
Combustion Turbine	Bogue (10, 11, 43, 56, 58, 63)	103.5	111
Combustion Turbine	Huntsbay (12)	32	15
Medium Speed Diesel	Huntsbay (300, 301)	60	30
Gas Combined Cycle	Old Harbour (41, 47, 50)	3x117 = 351	3x82 = 246
Coal	Huntsbay (57)	114	80
Coal	Rockfort (37)	114	80
Waste	Riverton (601)	45	31.5
Waste	Retirement (602)	20	14
Photovoltaic	Paradise 1 (401)	49.5	0
Photovoltaic	Paradise 2 (402)	30	0
Photovoltaic	Old Harbour (114)	30	0
Photovoltaic	Kelly's Pen A (403)	20	0
Photovoltaic	Micham (409)	25	0
Photovoltaic	Parnassus (411)	43	0
Wind 1	Wington I & II (202)	38.7	0
Wind 1	Rose Hill (500)	30	0
Wind 1	**Munro I (503)**	**3**	**0**
Wind 1	**Munro II (503)**	**34**	**0**
Wind 2	**Winchester (502)**	**98.5**	**0**
Co-generation	Appleton (604)	20.5	14.3
Co-generation	Monymusk (78)	15	10.5
Co-generation	Frome (606)	27.5	19.2
Dam	**Magohany Vale (710)**	-	-

		High Flow		Intermediate Flow		Low Flow	
		PGen (MW)	QMax (MVAr)	PGen (MW)	QMax (MVAr)	PGen (MW)	QMax (MVAr)
Hydro run-of-river	Rio Bueno (65)	2.5	1	1.52	0.61	0.41	0.16
Hydro run-of-river	**Maggoty Falls (25)**	**12.6**	**5.04**	**7.68**	**3.08**	**2.04**	**0.82**
Hydro run-of-river	Upper White River (64)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Lower White River (68)	4	1.6	2.44	0.98	0.65	0.26
Hydro run-of-river	Roaring River (59)	3.8	1.52	2.32	0.93	0.62	0.25
Hydro run-of-river	Constant Spring (91)	0.8	0.32	0.48	0.19	0.15	0.06
Hydro run-of-river	Ram's Horn (711)	0.6	0.24	0.36	0.14	0.11	0.04
Hydro run-of-river	Great River (115)	8	3.2	4.88	1.95	1.3	0.52
Hydro run-of-river	Laughlands (701)	2	0.8	1.22	0.49	0.32	0.13
Hydro run-of-river	Back Rio Grande (700)	10	4	6.03	2.41	1.89	0.76
Hydro run-of-river	Green River (702)	1.4	0.56	0.85	0.34	0.23	0.09
Hydro run-of-river	**Martha Brae (67)**	**12.90**	**5.16**	**2.62**	**1.05**	**1.55**	**0.62**
Hydro run-of-river	**Rio Cobre (703)**	**2.00**	**0.80**	**0.34**	**0.14**	**0.20**	**0.08**
Hydro run-of-river	**Dry River (704)**	**-**	**-**	**-**	**-**	**-**	**-**
Hydro run-of-river	**Negro River (705)**	**2.50**	**1.00**	**0.60**	**0.24**	**0.25**	**0.10**
Hydro run-of-river	Yallahs River (706)	2.60	1.04	1.60	0.64	0.37	0.15
Hydro run-of-river	Wild Cane River (707)	2.50	1.00	1.54	0.61	0.36	0.14
Hydro run-of-river	**Morgan's River (708)**	**2.70**	**1.08**	**0.64**	**0.26**	**0.27**	**0.11**
Hydro run-of-river	**Spanish River (709)**	**7.70**	**3.08**	**1.03**	**0.41**	**0.91**	**0.36**

Table IV-7: Alternative Generation portfolio of the 2030 With Renewable scenario

The following figures give a general recapitulation of installed capacity per energy source.


Installed Capacity,
Alternative Renewable Scenario
1000
900
800
700
600
500
400
300
200
100
0
63
888.5
0
82.4
197.5
65
204.2
Co-generation
Conventional
Hydro dam
Hydro run-of-river
Photovoltaic
Waste
Wind


Installed Capacity,
Corrected Renewable Scenario
1000
900
800
700
600
500
400
300
200
100
0
63
888.5
50
58.2
197.5
65
160.7
Co-generation
Conventional
Hydro dam
Hydro run-of-river
Photovoltaic
Waste
Wind

IV.4. RESULTS

IV.4.1. The 2030 Conventional plants scenario

IV.4.1.a Branch constraints

For each of the three rain periods identified for the run-of-river hydraulic power plants, 1000 N situations and 10 000 N-1 situations were simulated.

The table below presents the overloading criterion for this scenario, as defined in section 2.

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.0 %	0.0 %
"N-1" network (10,000 simulations)	4.01 %	4.17 %	7.91 %

Table IV-8: Overloading criterion, 2030 Conventional Plants scenario

IV.4.1.b Voltage constraints

For each of the three rain periods identified for the run-of-river hydraulic power plants, 1000 N situations and 10 000 N-1 situations were simulated.

The table below presents the voltage limit violation criterion for this scenario, as defined in section 2.

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	2.9 %	2.5 %	5.7 %
"N-1" network (10,000 simulations)	23.74 %	22.67 %	33.35 %

Table IV-9: Voltage limit violation criterion, 2030 Conventional Plants scenario

IV.4.1.c First analysis of the raw results

Those numbers will serve as a reference against which the situation with the integration of renewable can be compared.

Concerning the branch constraints, it is apparent here that there are absolutely no branch constraints in N situation. Concerning N-1 situations, the lesser the output of hydraulic run-of-river power plants, the more constrained the network is. Most of the run-of-river plants are located close to loads where no other form of generation exists. Their presence will then decrease the net load. Considering the location of renewable plants to be integrated in the 2030 With Renewable scenario, a similar effect can be expected.

Concerning the voltage constraints, N-1 results may seem alarming. However, it must be noted that all of these constraints are under-voltage constraints, and are then voltage-drops related. What's more, few buses make most of the constraint:

- The Port Antonio load (buses 48, 502, 71) is at the end of long lines, with no generation nearby. An important voltage drop is then inevitable.
- The Roaring River load (bus 66, 701, 59) and the nearby Cardiff (bus 109) and Ocho (bus 32) loads are also quite far from generators, considering the Roaring River hydro power plant cannot compensate for the Roaring River load. For this reason, they are primarily concerned by voltage drops too.

IV.4.2. The 2030 With Renewable scenario

IV.4.2.a Branch constraints

For each of the three rain periods identified for the run-of-river hydraulic power plants, 1000 N situations and 10 000 N-1 situations were simulated. It is reminded that presence of solar power requires separation between day and night simulations.

The tables below present the overloading criterion for this scenario, as defined in section 2.

Variations between original and new renewable scenarios greater than 1% are colored either in blue, if the new scenario gives better results, or in red, if the results are worse.

<u>Original renewable scenario:</u>

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.3 %	0.2 %
"N-1" network (10,000 simulations)	5.20 %	3.21 %	5.56 %

Table IV-10: Overloading criterion, 2030 With Original Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.2 %	0.0 %
"N-1" network (10,000 simulations)	3.04 %	2.73 %	2.67 %

Table IV-11: Overloading criterion, 2030 With Original Renewable scenario, night

Corrected renewable scenario:

	High Flow	Inter Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.3 %	0.2 %
"N-1" network (10,000 simulations)	4.44 %	3.43 %	5.75 %

Table IV-12: Overloading criterion, 2030 With Corrected Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.2 %	0.0 %
"N-1" network (10,000 simulations)	2.50 %	2.04 %	2.36 %

Table IV-13: Overloading criterion, 2030 With Corrected Renewable scenario, night

Alternative renewable scenario:

	High Flow	Inter Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.2 %	0.0 %
"N-1" network (10,000 simulations)	2.70 %	3.52%	5.59 %

Table IV-14: Overloading criterion, 2030 With Alternative Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.4 %	0.2 %
"N-1" network (10,000 simulations)	0.96 %	3.57 %	3.14 %

Table IV-15: Overloading criterion, 2030 With Alternative Renewable scenario, night

IV.4.2.b Voltage constraints[12]

The tables below present the voltage limit violation criterion for this scenario, as defined in section 2.

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	59.6 %	39.9 %	11.3 %
"N-1" network (10,000 simulations)	61.06 %	45.04 %	23.00 %

Table IV-16: Voltage limit violation criterion, 2030 With Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	75.9 %	57.4 %	28.7 %
"N-1" network (10,000 simulations)	78.03 %	59.47 %	36.05 %

Table IV-17: Voltage limit violation criterion, 2030 With Renewable scenario, night

IV.4.2.c First analysis of the raw results

Concerning the steady-state operational safety criterion, as expected, the renewable energy sources improve the results by generating energy closer to the load and thus reducing power flows on the transmission lines. These results seem to indicate that the objective of the Ministry of Science, Technology, Energy and Mining of Jamaica to accommodate 30% of renewables in electricity generation in 2030 is achievable without any specific increase of investments to be made on the transmission network.

The corrected and alternative scenarios have slightly better results in high flow period, especially the alternative portfolio in N-1 high flow period at night. This is due to the higher spreading of renewable installed capacity across the system, which reduces distances between generation and consumption. Still, in average, results are very close.

Concerning the voltage safety criterion, the numbers are very high and most of the constraints are over voltages at the Winchester wind farm connection point. These over voltages are due to the very high power output of this wind site. However, at this point, no capability of voltage control was implemented in the model. These problems can be tackled. This issue is addressed in the following section.

In the next section, the consultant investigates these raw results in more details and builds a comprehensive picture of the 2030 situation for the Jamaica electricity network. The consultant is then able to make recommendations for reinforcements on the Jamaica electricity network.

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[12] Results concerning the voltage for the corrected and alternative renewable scenarios are presented in the next chapter of this document, as these scenarios were directly implemented with voltage control capabilities in Winchester.

IV.4.3. Probability of instantaneous VRE penetration rate

The consultant has observed throughout its experience of operation of the French islanded networks that an instantaneous penetration rate for VRE lower than 30% does not have significant negative impact on the dynamic behaviours of electrical networks. This issue is addressed in more details in section 6 of this document.

As a reminder, in section 2, results showed for 2013 a potentially very high instantaneous penetration rate for variable renewable energy: the rate was higher than 30% in 43% of the cases for the 2013 with renewable scenario. This rate is defined as the share of VRE in instantaneous generated power. It gives an insight of the constraints set on the conventional units in terms of ancillary services, and more particularly in terms of frequency control (reserves, margins, inertia).

Concerning the 2030 with renewable scenario, this rate is significantly lower, reaching at maximum 37% against 50% in 2013, and less frequent, being higher than 30% in only 4% of the cases against 43% in 2013, as shown in the figure below. A lower VRE instantaneous penetration means that risk is reduced in case of unexpected frequency event on the network and less frequently above 30% means the period of risk is shorter during the year.

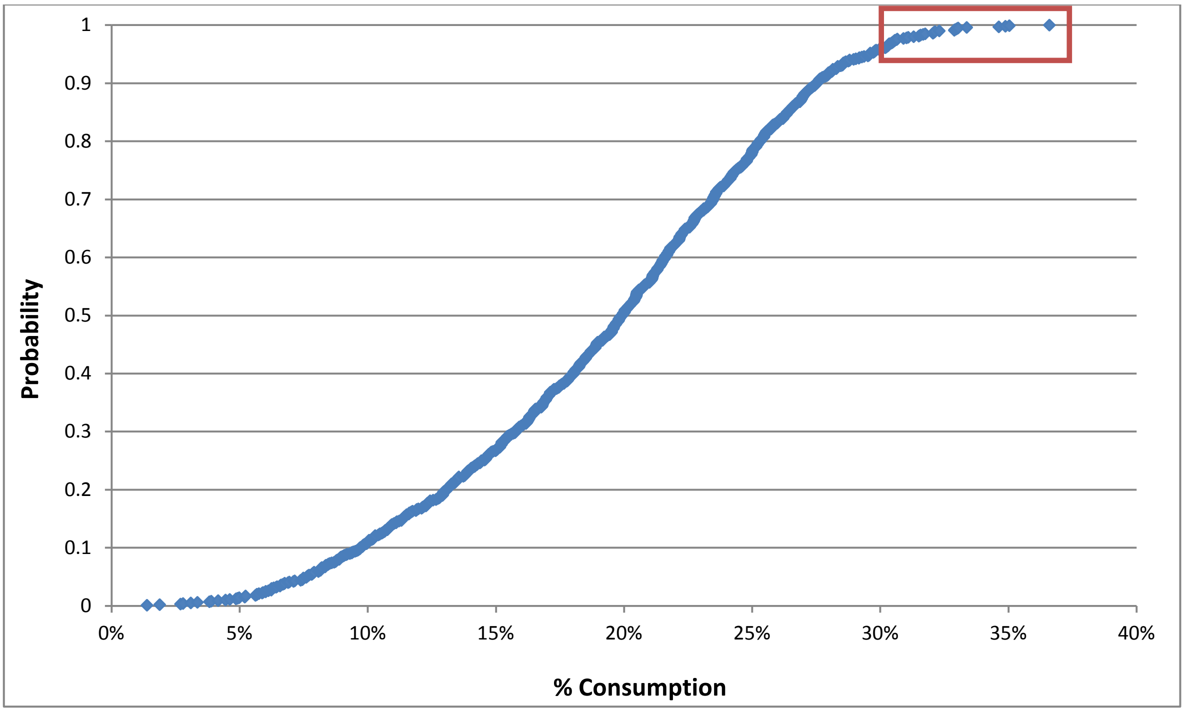

Figure IV-1: cumulative density function of instantaneous VRE penetration rate, day in 2030 With Original Renewable scenario

While results concerning the overloading criteria are similar from one renewable scenario to another, the alternative renewable scenario shows higher VRE installed capacity. The impact on the instantaneous penetration rate can be seen on the following figure.

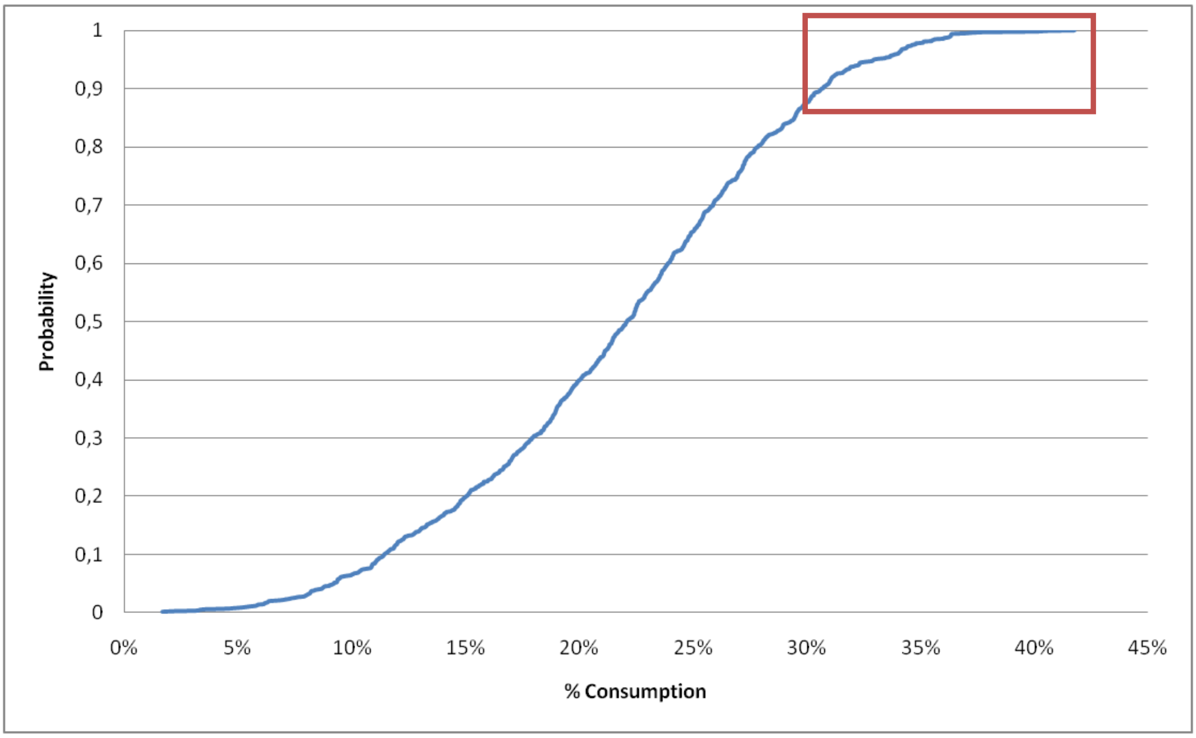

Figure IV-2: cumulative density function of instantaneous VRE penetration rate, day in 2030 With Alternative Renewable scenario

As a reminder, this Alternative Renewable Scenario differs from the Original Renewable Scenario concerning variable renewable energies by having a greater installed capacity of wind power – Winchester being at 98.5 MW against 75 MW in the base case scenario and Munro being at 37 MW against 3 MW in the base case – but has the same installed capacity of solar power.

The instantaneous VRE penetration rate reaches 41% at its maximum, against 37% in the original scenario, but more importantly, this rate passes across 30% in more than 12% of the cases. The risk zone for dynamic issues has increased in this alternative scenario.

V. COMPARISON OF SCENARIOS AND RECOMMENDATIONS FOR THE NETWORK IN 2030

V.1. VOLTAGE MANAGEMENT IN PRESENCE OF VRE

It is now worldwide accepted among the electricity utility community that VRE sources have the ability to participate to voltage management. It is made in various ways across the community, but many countries have already included, or have projects to include, in their grid code an obligation for VRE sources to contribute to ancillary services for voltage management.

Ability of wind turbines to contribute to voltage management depends on the selected technology. The consultant suggests to install Vestas V80 2MW turbines. This turbine, one the most sold on-shore wind turbine throughout the world, uses a doubly-fed induction machine. Typical (P,Q) capabilities of this kind of machine can be easily found in international literature. The following figure presents some examples.

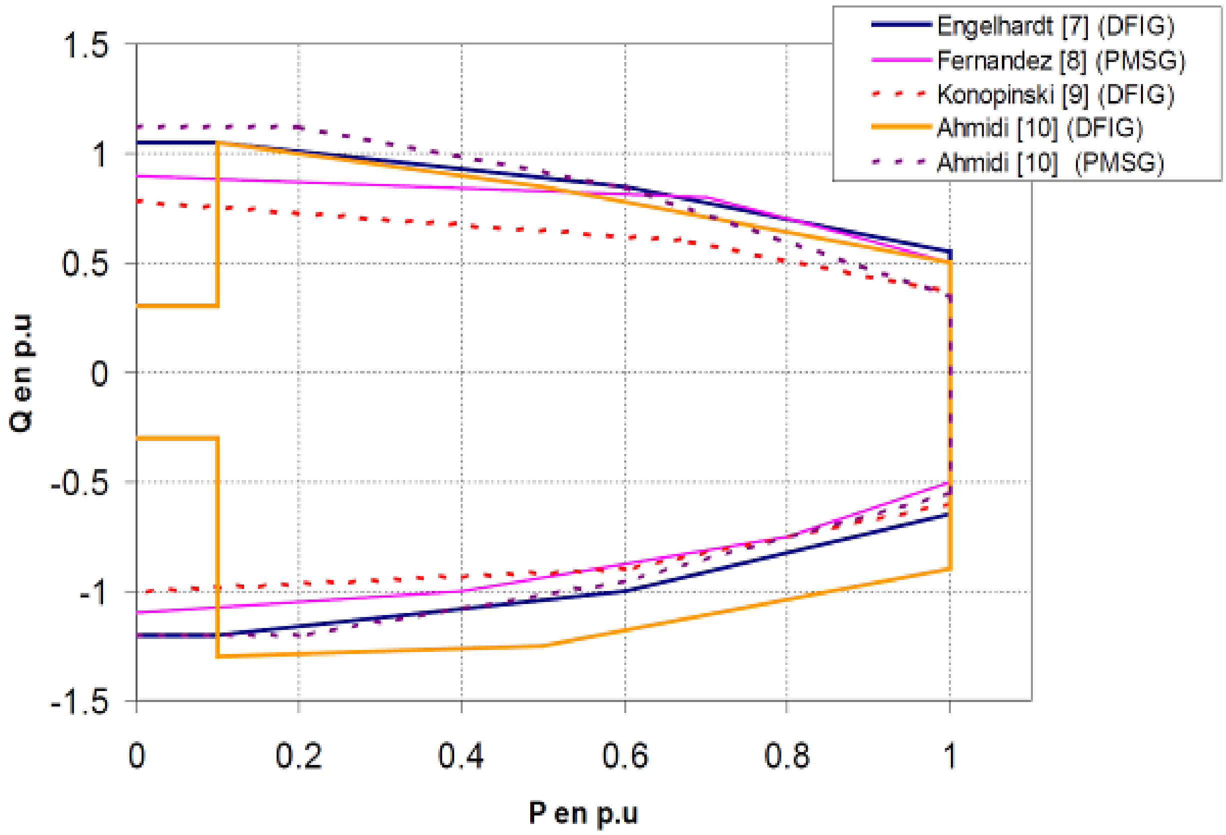

Figure V-1: typical (P,Q) characteristics of Doubly-Fed Induction Machine (DFIM)[13]

As it can be seen on the above figure, capability curve of a DFIM is not symmetrical: such a machine can go deeper in absorption regime than in furniture regime, meaning high voltage issues are easier to manage than low voltage ones with this kind of machine.

[13] Jerôme Duval, EDF R&D, 2011

On the other hand, ability of PV to contribute to the voltage management does not depend on the PV technology itself. Because of its direct nature, a PV installation requires a full ad-dc converter. And capability curves are directly depending on sizing of this converter. The sizing of the converter must thus meet requirements from the TSO, so that the installation can provide appropriate voltage management.

In this study, because of the uncertainty around this topic in the grid code, solar power does not contribute to voltage management at all. Concerning the wind power, limited capacity of voltage control has been consider in accordance with previous figure, only at Winchester.

V.2. STEADY STATE OPERATIONNAL SAFETY COMPARISON

V.2.1. Conventional scenario

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.0 %	0.0 %
"N-1" network (10,000 simulations)	4.01 %	4.17 %	7.91 %

Table V-1: Overloading criterion, 2030 Conventional scenario

V.2.2. Renewable scenarios

Original renewable scenario:

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.3 %	0.2 %
"N-1" network (10,000 simulations)	5.20 %	3.21 %	5.56 %

Table V-2: Overloading criterion, 2030 With Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.2 %	0.0 %
"N-1" network (10,000 simulations)	3.04 %	2.73 %	2.67 %

Table V-3: Overloading criterion, 2030 With Renewable scenario, night

Corrected renewable scenario:

	High Flow	Inter Flow	Low Flow
“N” network (1000 simulations)	0.0 %	0.3 %	0.2 %
“N-1” network (10,000 simulations)	4.44 %	3.43 %	5.75 %

Table V-4: Overloading criterion, 2030 With Corrected Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
“N” network (1000 simulations)	0.0 %	0.2 %	0.0 %
“N-1” network (10,000 simulations)	2.50 %	2.04 %	2.36 %

Table V-5: Overloading criterion, 2030 With Corrected Renewable scenario, night

Alternative renewable scenario:

	High Flow	Inter Flow	Low Flow
“N” network (1000 simulations)	0.0 %	0.2 %	0.0 %
“N-1” network (10,000 simulations)	2.70 %	3.52%	5.59 %

Table V-6: Overloading criterion, 2030 With Alternative Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
“N” network (1000 simulations)	0.0 %	0.4 %	0.2 %
“N-1” network (10,000 simulations)	0.96 %	3.57 %	3.14 %

Table V-7: Overloading criterion, 2030 With Alternative Renewable scenario, night

V.2.3. Conclusion from the power flow point of view

From these tables, two important elements must be noted:

- the Jamaica electricity network is not expected to encounter major issues with power flow management in 2030, indicating that currently the network has significant steady-state margin;
- renewables are not expected to deteriorate the situation in 2030; results are very close in average or, in other words, the recorded gaps between the two scenarios are not high enough to be significant.

V.3. VOLTAGE SAFETY

V.3.1. Conventional scenario

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	2.9 %	2.5 %	5.7 %
"N-1" network (10,000 simulations)	23.74 %	22.67 %	33.35 %

Table V-8: Voltage limit violation criterion, 2030 Conventional scenario

V.3.2. Renewable scenarios

Variations between original and new renewable scenarios greater than 0.5% are colored either in blue, if the new scenario gives better results, or in red, if the results are worse.

Original renewable scenario[14]:

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.1 %	0.1 %	0.2 %
"N-1" network (10,000 simulations)	9.63 %	9.06 %	12.91 %

Table V-9: Voltage limit violation criterion, 2030 With Renewable, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.1 %	0.3 %	0.0 %
"N-1" network (10,000 simulations)	4.90 %	6.22 %	9.62 %

Table V-10: Voltage limit violation criterion, 2030 With Renewable, night

[14] The figures presented in the above tables are different from the ones presented in section A-IV.4.2.b as voltage control capacity was implemented for the Winchester wind farm.

Corrected renewable scenario:

	High Flow	Inter Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.0 %	0.1 %
"N-1" network (10,000 simulations)	8.07 %	9.14 %	12.29 %

Table V-11: Voltage limit violation, 2030 With Corrected Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.1 %	0.0 %	0.0 %
"N-1" network (10,000 simulations)	3.59 %	5.66 %	9.12 %

Table V-12: Voltage limit violation criterion, 2030 With Corrected Renewable scenario, night

Alternative renewable scenario:

	High Flow	Inter Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.1 %	0.3 %
"N-1" network (10,000 simulations)	7.39 %	10.13 %	13.35 %

Table V-13: Voltage limit violation criterion, 2030 With Alternative Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.0 %	0.0 %
"N-1" network (10,000 simulations)	3.20 %	6.20 %	10.05 %

Table V-14: Voltage limit violation criterion, 2030 With Alternative Renewable scenario, night

It must be noted that all of the voltage limit violations are due to low voltages.

V.3.3. Conclusion from the voltage point of view

From these tables, two important elements must be noted:

- the Jamaica electricity network is expected to experience severe largely spread low voltage situations by 2030;
- renewables on the network improve the situation noted in the conventional scenario.

The corrected and alternative scenarios do not have significant impacts on the results. Small differences may be noted in high and intermediate flow period, but of course none of these changes remain in low flow period. In average, results are very close.

V.4. PROPOSED REINFORCEMENTS

V.4.1. Objective of the study

The main task assigned to the consultant is to evaluate the impacts, if any, of the development of renewable energy on the electricity network, from a steady-state point of view. In a practical manner, the goal is to evaluate if introducing renewable in the network can lead to an increase of required investments on this network.

Given the fact that the network expansion plan was not available, the consultant has suggested to run simulations on the 2030 network with the conventional scenario, then with the renewable scenario, to compare results and finally to identify the reinforcements to add to the worse scenario so that its results are equivalent to the ones of the best scenario.

V.4.2. Comparison

From the steady state operational safety results presented in the previous chapter, the consultant draws the conclusion that performance of the network in the two scenarios is equivalent from the power flows point of view, and that no additional reinforcements is required for this topic.

From the voltage safety results, the consultant identifies that additional reinforcements will be required if the conventional scenario was selected. The performance of the network in the conventional scenario is indeed worse than in the renewable one.

To locate and size these reinforcements, the consultant has analysed the constraints that occur on the network and has identified the main problems to solve. These problems are low voltages in:

- Roaring River when hydropower is not high enough
- Maggotty when the load is high
- Port Antonio because of its location

In these three substations, voltage support is required in order to reduce low voltage limit violations.

V.5. REINFORCEMENTS

The consultant recommends the following reinforcements to be implemented:

- 2x6 MVAr switchable capacitor banks connected to the distribution side in Maggotty;
- 8 MVAr switchable capacitor banks connected to the distribution side in Port Antonio, in replacement of existing capacitor banks;

- 8 MVAr switchable capacitor banks connected to the distribution side in Roaring River.

After implementation of these reinforcements, the consultant has performed the simulations again. The new results are presented in the tables below. As the most critical situation is during the day, only day results are shown. The conventional scenario has also been split into day and night so that clear comparison can be made.

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0%	0.0 %	0.0 %
"N-1" network (10,000 simulations)	2.60%	2.84 %	6.81 %

Table V-15: Overloading criterion, 2030 Conventional scenario with reinforcements, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0 %	0.3 %	0.2 %
"N-1" network (10,000 simulations)	5.20 %	3.21 %	5.56 %

Table V-16: Overloading criterion, 2030 Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.0%	0.0 %	0.0 %
"N-1" network (10,000 simulations)	8.09 %	7.95 %	13.74 %

Table V-17: Voltage limit violation criterion, 2030 Conventional scenario with reinforcements

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.1 %	0.1 %	0.2 %
"N-1" network (10,000 simulations)	9.63 %	9.06 %	12.91 %

Table V-18: Voltage limit violation criterion, 2030 With Renewable, day

Even if there seems to be slightly more constraints with renewables, the worst case is always conventional, low flow period. The consultant concludes that simulations show equivalent enough results in conventional and renewable scenario, after implementation of the proposed reinforcements to make the scenarios with and without renewables comparable. The objective is met.

Because there was not a significant difference in over loadings in the two scenarios, reinforcements were sized only to meet voltage limit violation criterion target. However, these reinforcements still have a slight downward effect on the overloading criterion.

V.6. COSTS OF THE PROPOSED REINFORCEMENTS

All cost estimates are built upon the following assumptions:

- Prices are DDP
- Import Duty 0%
- GCT 21.5%
- Customs User Fee 2%
- Standards Compliance Fee 0.3%
- Environmental Levy 0.5%
- Engineering 7%

Reinforcement	Material	Civil	Erection	Engineering	Total
Maggotty	569,707.04	161,700.00	216,406.20	66,346.93	1,014,160.17
Port Antonio	374,190.49	120,450.00	113,925.58	42,599.62	651,165.69
Roaring River	417,453.15	187,935.00	132,611.18	51,659.95	789,659.28

Table V-19: Cost estimates for the proposed reinforcements

Considering the nature of the reinforcements, a precise planning for their implementation does not seem required. The consultant recommends implementing these solutions any time before 2028.

V.7. GRID CODE RECOMMENDATIONS

As mentioned in section 2 and 4, all solar and wind power sites have been considered as fixed power factor generating units, with power factor of 1, including step-up transformers. Only one site is modelled differently, Winchester, because it has significant impact on the network and that it is obvious that the proposed wind turbines have the ability to control the voltage.

Consequently, in this study renewables do not have voltage control capabilities[15]. This is a very important point to notice. The consultant has made this hypothesis as it is a reasonable consideration regarding up to date power electronics technologies. However, it is very important that requirements for voltage control conditions are set in the appropriate section of the Jamaican Grid code to ensure renewable units will not deteriorate the voltage conditions on the network.

The consultant thus specifically suggests that all renewable installation should be required capabilities of controlling their power factor at HV connection bus, within a limit to be chosen locally, and that all installation should provide fault-ride-through capabilities during short-circuits and voltage drops. These considerations basically exclude any installation of wind turbine with simple asynchronous machine without power electronics.

[15] Renewables apart from Winchester as this site is likely to create over voltage conditions and will be specifically required to have capability of reducing the voltage at the connection bus.

VI. MANAGING THE DYNAMIC IMPACTS OF VRE

In chapter II.4. Target for Penetration Rate on a short term horizon and chapter IV.4.3. Probability of Instantaneous VRE penetration rate, cumulative density functions of instantaneous VRE penetration rate were presented, respectively for 2013 and 2030. The quantity varies from its minimum to its maximum and the cumulative density function is a continuous monotone increasing function between 0 and 1. In the present case, these curves give the cumulated probability for solar and wind power together to represent a share of the generated power at any instant during the year.

Very high instantaneous shares of VRE in the generated power can have various impacts on the operation of the system, given that they cannot participate to frequency control. These impacts can be listed under two main categories:

- Impacts on the short-term balancing, that we can identify as slow-dynamic impacts
- Impacts on the frequency behaviour, that we can identify as fast-dynamic impacts

Both of these two categories require special attention when commissioning large amount of VRE. Dynamic aspects were not part of the scope of this study, thus the main goal of this chapter is only to give general ideas about the problems the Jamaican system might face and the possible associated solutions.

The consultant wishes to highlight that the basic principle of electrical system planning is based on steady-state analysis for sizing and optimization of the investments, and dynamic analysis to confirm that selected solutions are feasible and will meet all operation safety criteria. Dynamic analysis is usually made once the planned generation portfolio and network are known and as goes commissioning of new units and VRE.

VI.1. SLOW-DYNAMIC IMPACTS

In this part are addressed short-term balancing issues, on a time scale between several tens of minutes to several hours.

Commissioning large amount of VRE in an electrical system increases the variability of the net load to be served by conventional generating units. In order to maintain balance between generation and consumption, conventional generating units have to compensate variations in the net load by adjusting the generated power. Increasing the variability of the net load means that conventional power plant will face stiffer up and down ramps in active power to follow. Generation expansion plan must then take into consideration the requirement for flexibility the conventional units will have to meet in order to accommodate the planned VRE portfolio. This issue has been addressed by the IEA in 2012 and shows that proper use of hydropower and fast reacting units allow integration of very large amount of VRE in electrical systems.

If the variability increases and the conventional generating units have to adjust their power output more often and more rapidly, they are also likely to reach their minimum power output more often. If minimum power outputs of conventional power plants are set with unnecessary margins, as it used to be the case in many countries including France, the system operators might face situations where they either have to curtail VRE, if technically possible, or shut off conventional generating units too often. As shut off - start up cycles and VRE curtailment have significant costs and can induce penalties for the TSO, minimum power outputs of conventional power plants must be carefully selected for existing ones and set as requirement to meet for ones to be build.

In day to day operation, predicting the load to be served is necessary to adjust and optimize operating schedules of the conventional power plants and operation of the network. These predictions are submitted to various uncertainties, linked to the demand, the generation or even to market conditions. These uncertainties create some risks for the balancing of the system and these risks require to be covered. The very name of this coverage can vary from one country to another; the consultant will here use the word margin. It is very important to notice the difference between margins, that are used to cover uncertainty of prediction in normal operation conditions and reserves that are used to cover abnormal operation conditions, mainly due to the loss of a generating unit.

Last significant impact of VRE on short-term balancing is the introduction of additional uncertainty in predicting the net load to be served at different time scale in day to day operation. This uncertainty directly comes from the difficulty of predicting power outputs from VRE due to weather variations. On an overall system scale, up to date weather forecast systems can maintain the error on VRE power output day-ahead predictions under 8% of VRE installed capacity. For large integration of VRE sources, it is necessary to consider this uncertainty to evaluate whether existing margin requirements are sufficient or not.

From the slow-dynamic impact perspective, it must be noted that the alternative renewable portfolio carries a risk for the system. Specific studies must be conducted, but it is obvious that a hydro dam with a certain water reservoir would be Jamaica’s best option to balance intermittency of variable renewables.

VI.2. FAST-DYNAMIC IMPACTS

In this part are addressed issues concerning the behaviour of the system’s frequency, on a time scale between several tens of milliseconds to several minutes.

High instantaneous VRE penetration rates have two significant impacts on the frequency behaviour:

- Relocation and increase of active power reserves for each conventional unit;
- Reduction of the overall inertia of the system.

Active power reserves are usually required to meet the maximum power output of the biggest generating unit in the system. Because VRE are spread over them territory, it is very unlikely that one VRE source can become this biggest unit and consequently lead to resize the reserves. VRE are nevertheless not capable – so far with up to date technology – of contributing to frequency management. The corresponding capability of frequency management must then be covered by conventional units. This effect leads to relocate the reserves on fewer generating units and to increase the reserve per machine for these units. This serves as an additional criterion that the conventional units have to meet in order to accommodate large amount of VRE.

The effect of VRE sources is the reduction of the system’s inertia. This effect has two consequences: first, during a fast-dynamic event, the frequency can reach lower limits in case of loss of generation and higher limits in case of loss of load. Dynamic studies must then be conducted to evaluate these lowest and highest points the frequency can reach on a single event. The second consequence is the introduction of a noise in the frequency signal, at all time in normal operation. This noise can lead to a reduction of the quality of the electricity signal itself; some industrial activities can be very sensitive to these issues. As for today, the only option to avoid deteriorating the system’s inertia is to switch from PV technologies to Concentrating Solar Power Plant (CSP), which is currently more expensive. Except CSP, there is no industrial solution to this problem other than limiting the instantaneous penetration rate of VRE. However, there are several tracks under investigation such as flying wheels, fast response storage and inertial contribution from VRE.

From the fast-dynamic impacts, it must be noted that, in order to avoid over-concentration of the primary reserve on conventional units, run-of-river plants might be forced to provide primary reserve to the system, leading to a loss of valuable resource. The alternative renewable scenario is particularly sensible to this issue.

VI.3. EDF'S OPERATION EXPERIENCE

EDF is undergoing the same process in the French Islands: the French government has set specific targets for electricity generated from VRE in each of these territories and EDF is responsible for adapting and operating these islanded systems.

EDF has worked on VRE integration for the last ten years and has adopted an operation rule since 2008, which allow curtailment of VRE sources when their instantaneous penetration rate exceeds 30%. This rule was set in order to make sure that curtailment of renewables, when operational safety was not 100% guaranteed, would not lead to financial compensations for private players and economic losses for the system operator.

From the grid code point of view, EDF has been confronted to requirement for voltage and harmonics management, but has never operated with ancillary services for frequency control. This field remains largely in research & development.

VII. ECONOMIC ASSESSMENT OF THE SELECTED PORTFOLIO

The economic assessment of the selected portfolio has been conducted by Hinicio in order to help the MSTEM get a better picture of the real economic impacts of introducing 30% renewable by 2030, compared to a business-as-usual trajectory.

The question has been analysed from two distinct perspectives. First, so called "Levelised Costs of Electricity" (LCOE) have been calculated for each of the different types of new capacities implemented between 2013 and 2030, in both scenarios (with and without renewables).

However, LCOEs do not capture the system costs of adding renewables, i.e. the costs induced by changes in the way the rest of the production mix has to be operated. Therefore, in a second step, first (and simplified) estimates of the overall costs of each of the two scenarios, including investment and running expenditures and fuel costs will be presented, thus providing orders of magnitude of the additional costs incurred by renewable energy compared to the reference case.

Importantly, inflation has not been factored in, as is usually the case in LCOE calculation and in accordance to the calculations made in the 2010 Generation Expansion Plan. A standard discount rate of 11.95% has been considered, as defined by the OUR for the entire Jamaican electricity sector. Additionally, all calculations and results presented in this section are net of government intervention (tax and subsidies). Said differently, they represent the costs to the Jamaican economy as a whole, and are not restricted to the costs to its electricity sector.

VII.1. LEVELIZED COSTS OF ELECTRICITY

VII.1.1. Definitions and assumptions

VII.1.1.a Definition of LCOE

The notion of Levelized costs of electricity (LCOE) is a metrics that is commonly used to compare the unit cost of generating electricity with different technologies over their entire lifetime.

In fact, for each power source, the LCOE equals the sum of all discounted costs divided by the total electricity production adjusted for its economic time value. In other words, the LCOE is strictly equal to the electricity price at which the owner of the generating asset would precisely break-even at the end of the project lifetime.

The LCOEs has been calculated with the following formula:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}}$$

Where:

- LCOE: Levelized Cost of Electricity in US$/MWh
- I_0: Total Investment Cost in US$
- A_t: Annual cost in year t (including: fixed and variable O&M, fuel costs and carbon costs)

- M_{el}: electricity output in year t in MWh
- i: discount rate
- n: economic lifetime of the project
- t: year of operation

VII.1.1.b Costs assumptions

The following cost assumptions have been made:

	CAPEX (US$/kW)	Fixed-OPEX (US$/kW)	Variable OPEX (US$/MWh)
Hydro (run-of-river)	3500	50	0
Hydro (dam)	3500	45	0
Wind (short-term)	2 080	0	10
Wind (mid-term)	1 826	0	10
Wind (long-term)	1 699	0	10
Solar PV (short-term)	2 689	6,5	0
Solar PV (mid-term)	2 096	6,5	0
Solar PV (long-term)	1 505	6,5	0
Biomass	3 000	120	4,25
Waste (short-term)	5 900	333	27
Waste (mid and long-term)	5 251	333	27
Combustion turbine	870,00	12,48	3,70
NGCC	1 317,00	12,84	2,53
Coal Unit	3 019,00	28,80	5,00

For renewable energies, the sources of information are the same as in section 3.2.1 (mainly IRENA). Average values have been assumed whenever necessary. As for conventional technologies, data have been taken from the 2010 Generation Plan. CAPEX for hydropower were given by the MSTEM.

Grid connection costs are included in the CAPEX component. Decommissioning has not been included, which is probably of very small impact anyway, given the high discount rate used in the calculations.

VII.1.1.c Technical assumptions

The following assumptions have been made:

	Lifetime (year)	Construction time (year)	Efficiency
Hydro (run-of-river)	40	1	-
Hydro (dam)	40	4	-
Wind	25	1	-
Solar PV	25	1	-
Biomass	25	2	22.55%
Waste	25	2	-
Combustion turbine (ADO)	25	1	34%
CCGT	25	3	47%
Coal Unit	35	4	37%

Similar to the previous section, assumption regarding the lifetime of renewable and conventional capacities have been based respectively on the series of report by IRENA on the one hand and the assumptions used in the 2010 Generation Plan (efficiencies. Construction times used were taken from a recent report by the UK Department of Energy and Climate Change[16]. Efficiencies also rely on the 2010 Generation Plan.

VII.1.1.d Fuel costs and sensitivity analysis

There is a large degree of uncertainty related to the investment costs whether present or future. For that reason, sensitivity analyses have been conducted for all power sources on the CAPEX with large ranges of variations: [-30%; 30%] in general, except for hydro ([-50%; +50%]) where the uncertainty is even larger (based on the literature).

When it comes to fuel costs, the following numbers have been used in the calculation:

- ADO: 100 – 125 – 150 – 175 – 200 US$/BBL (delivered price).
- Coal: 90 – 140 – 190 US$/ton (delivered price).

ADO and coal prices are globally consistent with the numbers that were used in the 2010 Generation Expansion Plan.

For the sake of simplicity, constant fuel and carbon costs have been assumed over the entire lifetime of the technologies under scrutiny. Indeed, LCOE are not designed to provide an accurate cost of production, which depends on too many external factors and unknowns, but rather ranges of reasonable numbers as well as cost reduction trends.

Importantly, no fuel cost has been assumed for biomass and waste-to-energy power plants. The strong assumption is made that it is the owner of the facility (rum factory, garbage dump…) who will implement and own the projects, with therefore an easy access to the raw material at no cost. This assumption will also be used in the modelling of the entire Jamaican electricity sector (see section VII.2).

Finally, the capacity factor is also a key factor affecting the LCOE for certain technologies. Sensitivity calculations on the capacity factor have therefore been done whenever relevant.

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[16] *Electricity Generation Costs, October 2012.*

VII.1.2. Results of LCOE calculations

VII.1.2.a Hydropower

Hydropower (run-of-river):

LCOE (US$/kWh)		Capacity factor		
		55%	**60%**	**65%**
CAPEX	**-50%**	62	57	52
	-25%	84	77	71
	0%	106	97	89
	+25%	128	117	108
	+50%	149	137	126

Hydropower (dam):

LCOE (US$/kWh)		Capacity factor		
		45%	**50%**	**55%**
CAPEX	**-50%**	94	76	63
	-25%	130	104	87
	0%	166	133	111
	+25%	202	162	135
	+50%	238	191	159

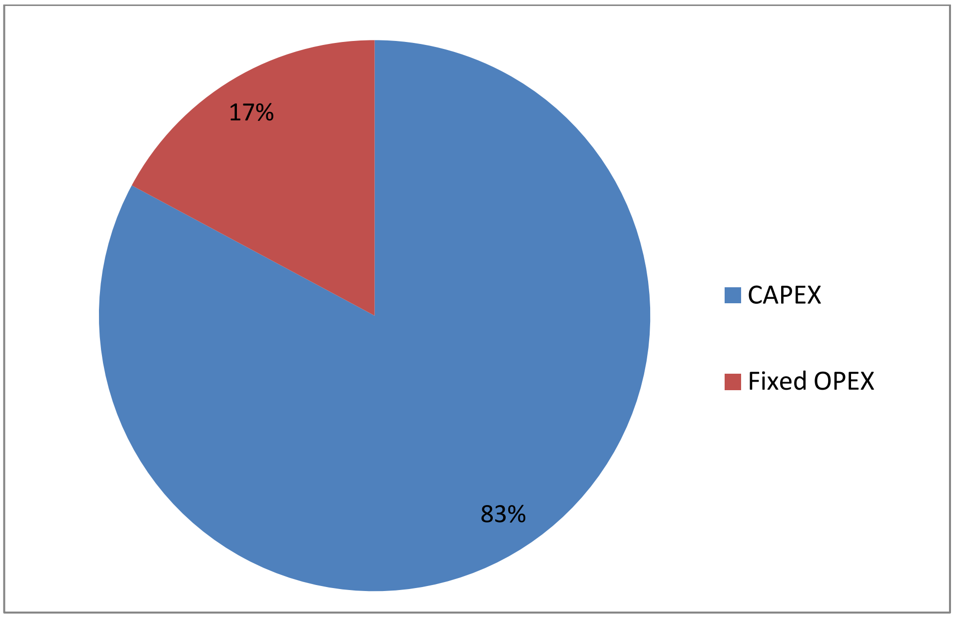


Figure VII-1: Typical LCOE break-down of run-of-river hydro (capacity factor: 60%, CAPEX: US$3500/kW)

VII.1.2.b Wind power

Short-term:

LCOE (US$/kWh)		Capacity factor		
		20%	**30%**	**40%**
CAPEX	**-30%**	115	80	62
	-15%	137	95	74
	0%	160	110	85
	+15%	182	125	96
	+30%	205	140	107

Mid-term:

LCOE (US$/kWh)		Capacity factor		
		20%	**30%**	**40%**
CAPEX	**-30%**	102	71	56
	-15%	122	84	66
	0%	141	98	76
	+15%	161	111	86
	+30%	181	124	95

Long-term:

LCOE (US$/kWh)		Capacity factor		
		20%	**30%**	**40%**
CAPEX	**-30%**	96	67	53
	-15%	114	79	62
	0%	132	91	71
	+15%	151	104	80
	+30%	169	116	89

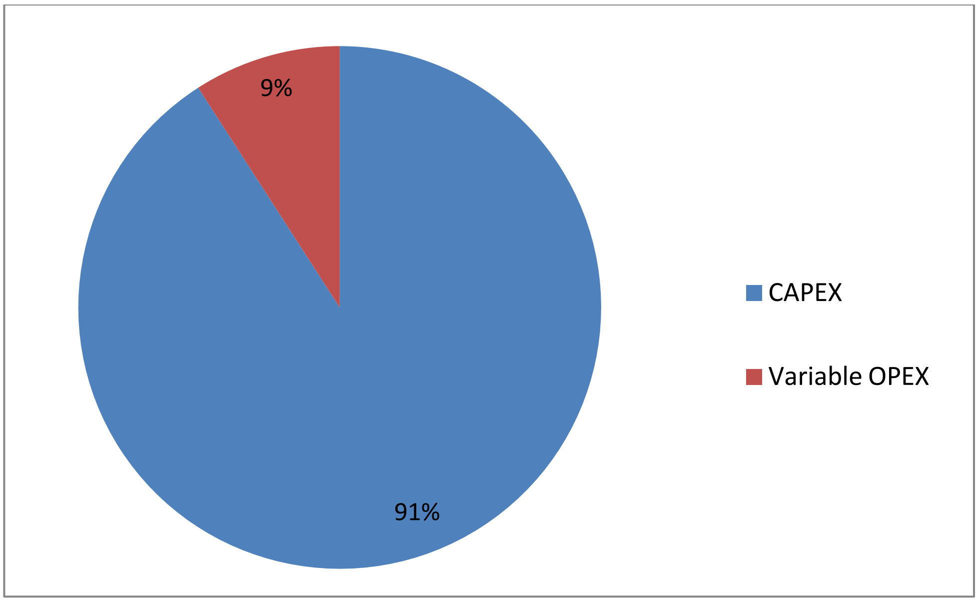


Figure VII-2: Typical LCOE break-down of wind power (capacity factor: 30%, CAPEX: US$2080/kW)

VII.1.2.c Solar PV

Short-term:

LCOE (US$/kWh)		Capacity factor		
		15%	**20%**	**25%**
CAPEX	**-30%**	186	139	111
	-15%	224	168	135
	0%	263	197	158
	+15%	302	226	181
	+30%	340	255	204

Mid-term:

LCOE (US$/kWh)		Capacity factor		
		15%	**20%**	**25%**
CAPEX	**-30%**	146	109	87
	-15%	176	132	106
	0%	206	155	124
	+15%	236	177	142
	+30%	266	200	160

Long-term:

LCOE (US$/kWh)		Capacity factor		
		20%	**30%**	**40%**
CAPEX	**-30%**	106	80	64
	-15%	128	96	77
	0%	149	112	90
	+15%	171	128	103
	+30%	193	144	116

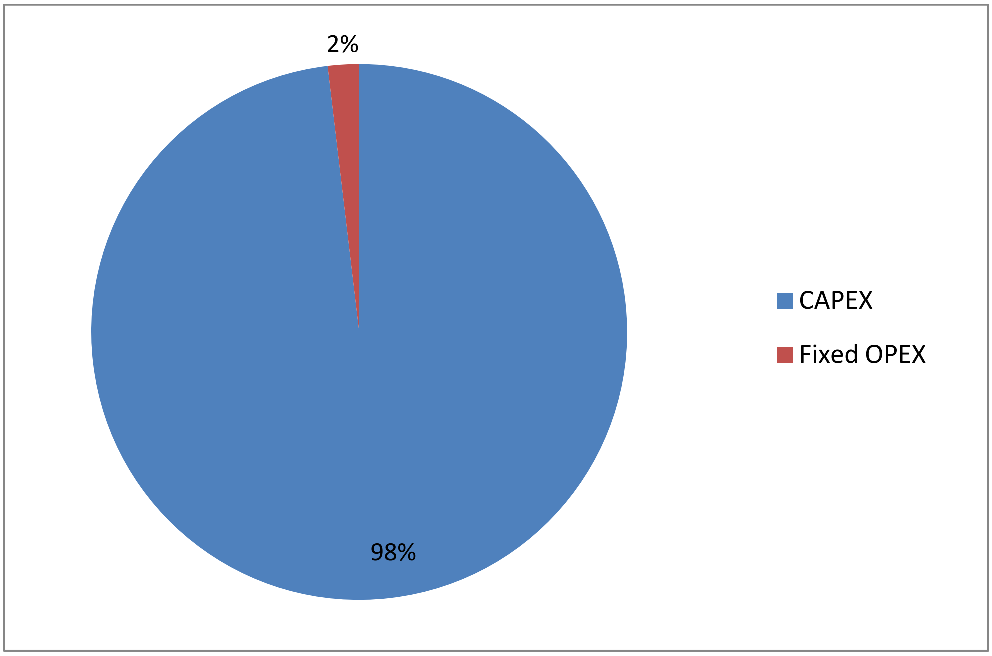


Figure VII-3: Typical cost break-down of solar PV (capacity factor: 20%, CAPEX: US$2689/kW)

VII.1.2.d Biomass

LCOE (US$/kWh)		Capacity factor			
		55%	**65%**	**75%**	**85%**
CAPEX	**-30%**	87	75	65	58
	-15%	100	85	74	66
	0%	112	96	84	74
	+15%	125	106	93	82
	+30%	137	117	102	90

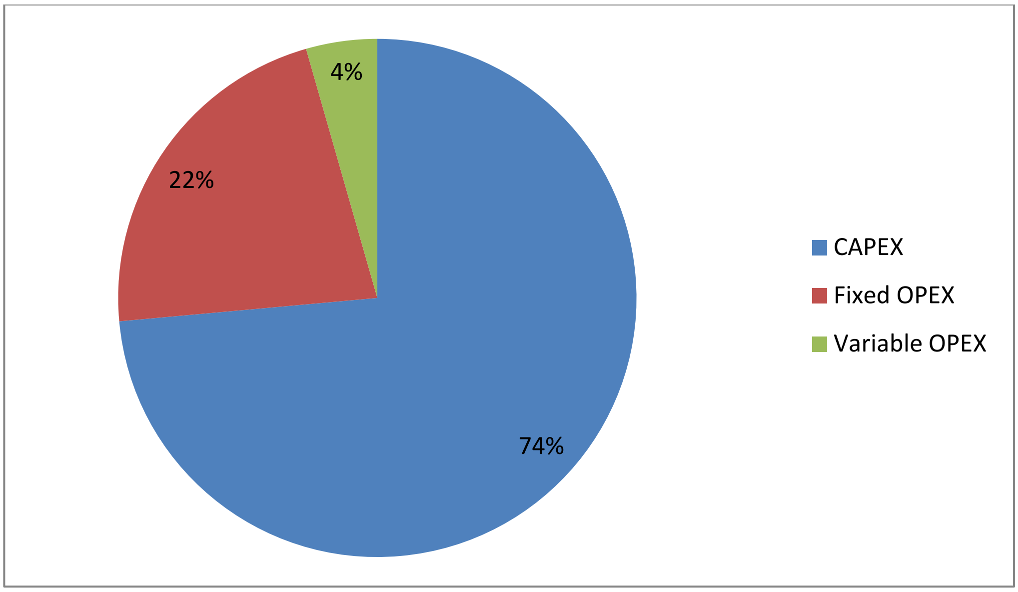


Figure VII-4: Typical LCOE break-down of a biomass power plant (capacity factor: 65%, CAPEX: US$3000/kW)

VII.1.2.e Waste-to-energy

Short-term:

LCOE (US$/kWh)		Capacity factor		
		75%	**80%**	**85%**
CAPEX	**-30%**	162	153	146
	-15%	180	170	162
	0%	198	187	178
	+15%	216	204	194
	+30%	234	221	209

Mid-term:

LCOE (US$/kWh)		Capacity factor		
		75%	**80%**	**85%**
CAPEX	**-30%**	153	145	138
	-15%	169	160	152
	0%	185	175	166
	+15%	201	190	180
	+30%	217	205	194

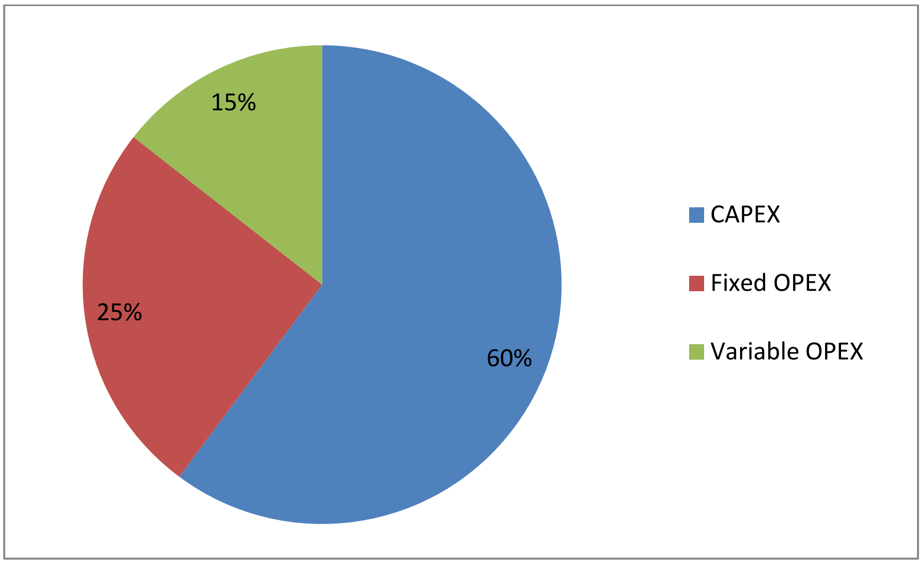


Figure VII-5: LCOE break-down of a waste-to-energy power plant (capacity factor: 80%, CAPEX: US$5900/kW)

VII.1.2.f CCGT (running on ADO)

In accordance to the simulation outcome, the capacity factor is assumed to be 49%.

LCOE (US$/kWh)		***ADO price (delivered)***		
		100US$/BBL	125US$/BBL%	150US$/BBL
CAPEX	**-30%**	173	207	241
	-15%	179	214	248
	0%	186	220	264
	+15%	193	227	261
	+30%	199	233	268

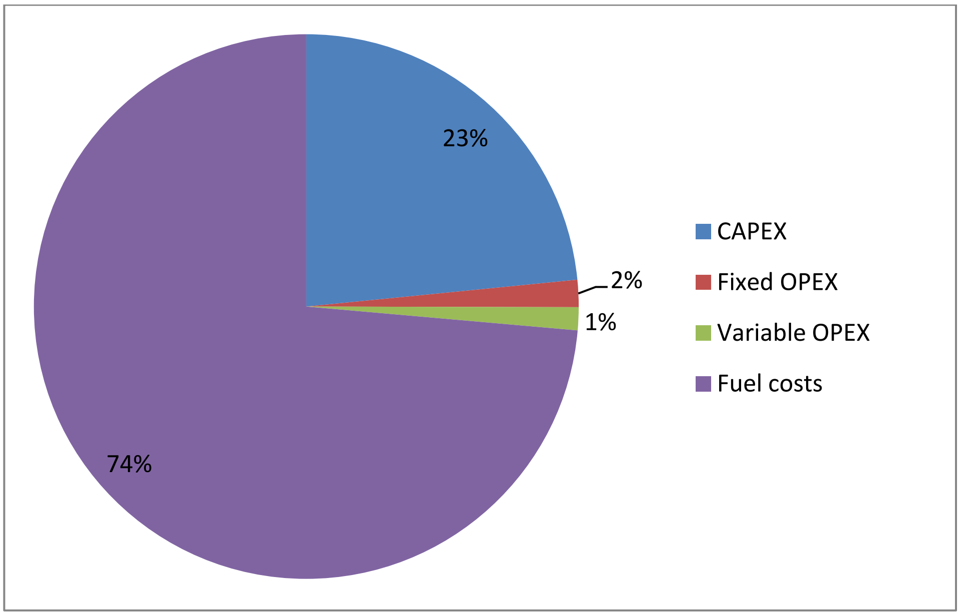


Figure VII-6 - Typical LCOE breakdown of a NGCC power plant running on ADO (ADO price: US$100/BBL, CAPEX: US$1317/kW)

The MSTEM has also provided, during the final assignment of the consultant in Jamaica, cost fuel for a CCGT running on LNG. The LCOE have been updated accordingly.

LCOE (US$/kWh)		***LNG price (delivered)***		
		100US$/BBL	125US$/BBL%	150US$/BBL
CAPEX	**-30%**	98	101	109
	-15%	104	108	115
	0%	111	114	122
	+15%	117	121	128
	+30%	124	128	135

VII.1.2.g Coal units

The capacity factor is assumed to be 85%.

LCOE (US$/kWh)		***Coal price (delivered)***		
		90US$/ton	140US$/ton	190US$/ton
CAPEX	**-30%**	85	104	124
	-15%	94	113	133
	0%	103	122	141
	+15%	111	131	150
	+30%	120	140	159

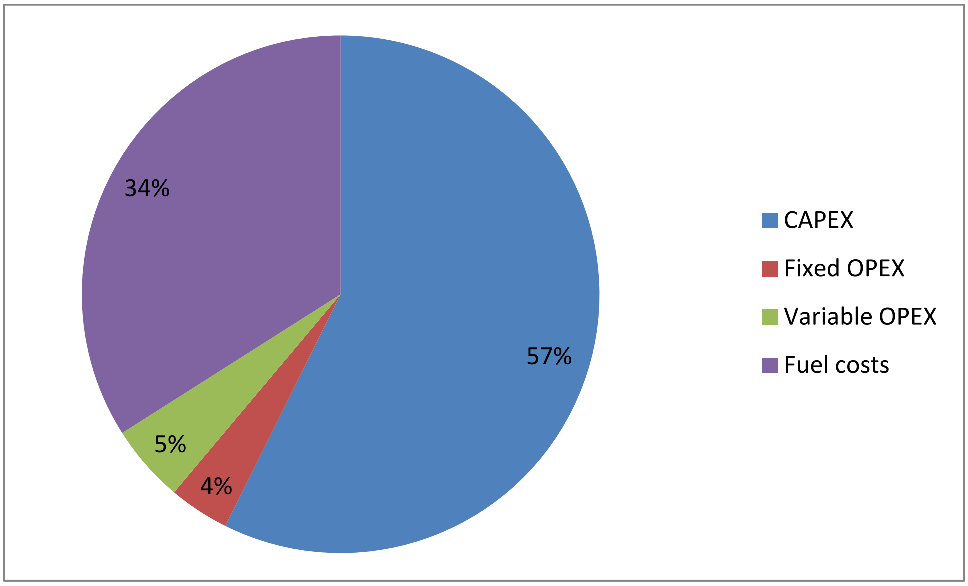


Figure VII-7 - Typical cost breakdown of a coal unit (coal price: US$90/ton, CAPEX: US$3019/kW)

VII.1.2.h Combustion turbine (running on ADO)

Combustion turbines are mostly used for peak power in the model and have therefore a very low capacity factor of just a few percentage points. For that reason, the LCOE is extremely high (over US$1300/kWh in all cases), far beyond those of other technologies under consideration in the study. It has not been judged useful to include the detailed results of the calculation here as comparing combustion turbine to other sources on a LCOE basis does not really make sense in our opinion as combustion turbines are in any event necessary in the current Jamaican electricity mix as peak capacities, and renewable will not come as a substitute for that particular purpose.

It would however make sense to compare the costs of combustion turbine to the costs of other alternative technologies or concepts used to supply electricity and/or reduce consumption during peak time, in particular energy storage and smart grid, but that is beyond the scope of this study.

VII.1.3. LCOEs comparison

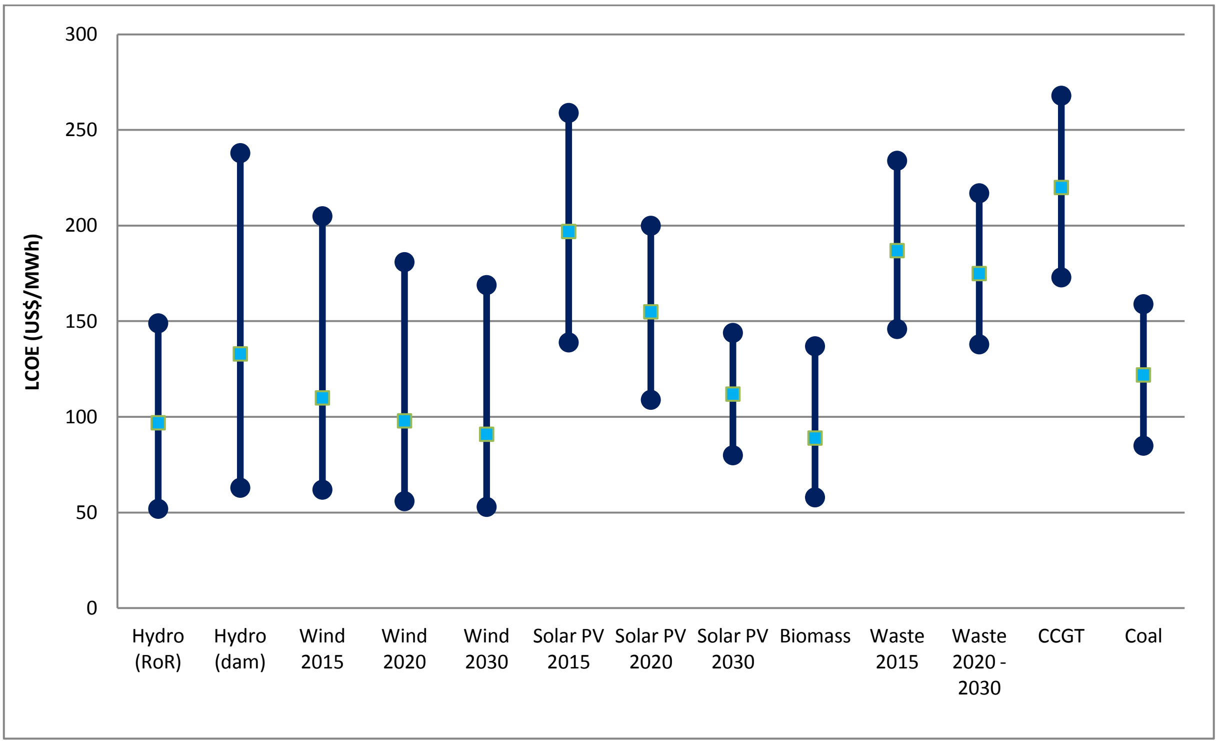


Figure VII-8 – Comparison of LCOEs for the technologies with CCGT on ADO (source: Hinicio)[17]

This graph summarizes the LCOE of each power source, with a min-max range, as well as a median value, based on the sensitivity analysis performed.

A coal unit is clearly much cheaper than a CCGT power plant under all fuel costs and technology costs assumptions. While the capacity factor assumed is significantly lower for the CCGT power plant (49%) compared to the coal unit (85%), we do not expect the LCOE of the CCGT power plant to drop proportionally with an increase in the utilization factor due to the prominence of fuel costs in the LCOE (74%, see section VII.1.1.g). Indeed, when the capacity factor is increased to 85%, the LCOE only drops from US$186/kWh to US$166/kWh, all other things remaining equal. It should however be noted that the assumptions made with regard to efficiencies of both coal and CCGT plants, which rely on the data used in the 2010 Generation Expansion Plan seem optimistic for the coal unit and pessimistic for the CCGT plant. With coal prices at and assuming a 35% efficiency (instead of 37%), the LCOE of the coal unit increases from US$103/MWh to US$105/MWh. Now assuming ADO prices at US$100/BBL and a 50% efficiency (instead of 47%), the LCOE of the CCGT power plant drops from US$186/MWh

[17] Note: for CCGT and coal no carbon price is assumed. For solar, the capacity factor is chosen at 20%, which is the global average in each of sites of interest identified in Jamaica.

to 178US$/MWh. 166US$/MWh can even be reached with a 55% efficiency. If we now assume that that very same unit is used with a 85% capacity factor, then the LCOE is further reduced to US$146/MWh.

Renewables are globally already cost competitive with CCGT and coal under our assumptions. Hydro is clearly the cheapest. Wind is also very affordable thanks to a relatively high capacity factor in Jamaica (30 to 40% for most sites). Biomass is also under US$100/kW although the cost would probably move upward should fuel costs be factored in. Waste-to-energy and solar have the highest LCOEs, despite a potentially drop for solar if cost reduction objectives are achieved in the mid-to-long term.

Finally, it is noteworthy that the series of pie-charts detailing the cost breakdown of each energy source reflect the generally different cost structure of renewable energy plants versus conventional ones. Renewables are capital intensive but have low running costs and fuel expenses. Conventional plants on the other hand have generally lower CAPEX but fossil fuel expenses represent a very large part of their LCOEs. Therefore, the uncertainty regarding security of fuel supply and fuel prices can have potentially a very significant impact on final real cost of generating electricity, while it is much more easily predictable in the case of renewables.

Moreover, because of those differences in cost structure, renewable are intrinsically penalized compared to conventional sources when it comes to financial modelling using discounted values, especially when high discount rates are used, as it is the case in Jamaica. Discount rates tend to over-value the present over the future. Therefore lower CAPEX – higher OPEX energy sources, such as conventional plants have an advantage over high CAPEX – low OPEX, such as renewables. And the higher the discount rate, the higher the distortion.

It should be noted that the calculation of hydropower costs have been based on new data provided by the MSTEM and result in an LCOE that is very close to the one of coal, which is surprisingly high according to the consultant's experience.

Additionally, and perhaps most importantly, in accordance with the MSTEM, the LNG cost are based on the assumptions that were made in the 2010 Generation Expansion Plan, adding on top of the projected natural gas market price an extra US$2.50/MMBtu to cover freight charges, LNG infrastructure and gas pipe line costs. Even if assessing the accuracy of this assumption is very clearly out of the scope of the present study, in the case of the scenarios described in the following, it is the consultant's opinion that the extra cost would in fact be much higher than US$2.50/MMBtu. This means that the LCOE of CCGT running on LNG presented on figure VII-9 below most likely do not reflect reality. As a consequence, the results provided here should not be viewed under any circumstance as a recommendation from the consultant to develop LNG in Jamaica.

The table below shows updated LCOE including CCGT running on LNG. These results do not reflect the consultant opinion, as the consultant has no information to evaluate the costs of LNG infrastructure in Jamaica.

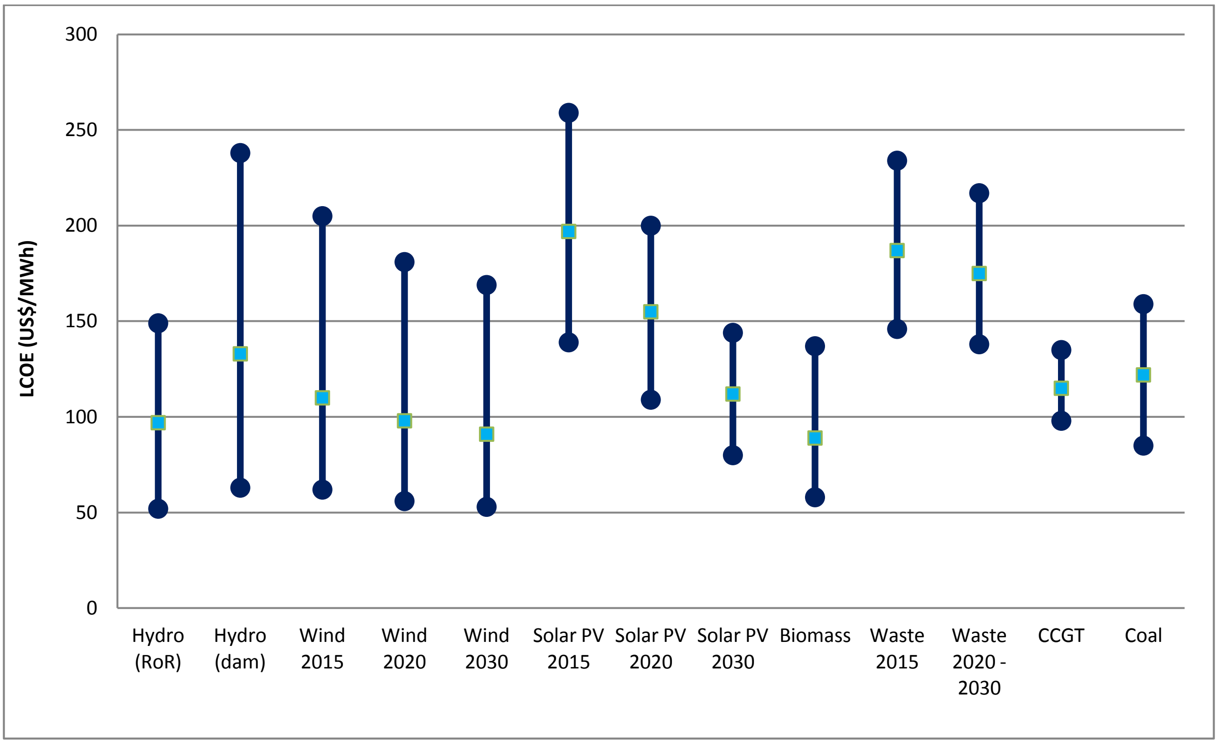


Figure VII-9: Comparison of LCOEs for the technologies with CCGT on LNG (source: Hinicio)

VII.2. ECONOMIC IMPACT OF A 30% RENEWABLE TARGET

VII.2.1. Definitions and assumptions

VII.2.1.a General principles of the economic modelling

The objective of this section is to assess the cost of implementing a 30% renewable energy target compared to a business-as-usual scenario from a systemic standpoint. Contrary to the previous section, generating costs of renewables and other technologies are not evaluated in isolation. The entire electricity sector of Jamaica is analyzed from 2013 through 2030, including both production and network reinforcements. On the production side, both running expenses (O&M, fuel and carbon costs) as well as investments in new capacities are considered. As for the network, only new investments are integrated in the calculation, but without any additional operational expenses (which would likely be negligible anyway compared to the other cost components).

A simplified timeline has been elaborated for this purpose:

- Short-term: 2013-2015
- Mid-term: 2016-2025
- Long-term: 2025-2030

For each of those periods, the electricity mix and production break-down at the power plant level will be assumed constant. Firstly, the short-term 2013-2015 window will be a “photography” of the current 2013 situation. Secondly, EDF’s modeling team has calculated an intermediate 2021 state for the Jamaican electricity system. These data (electricity mix and production output of each power plant) will be used in the medium-term from 2016 to 2025. For new renewable energy plants added during this timeframe, start of production is assumed in 2016. In contrast, new conventional power plants are added following the exact planning defined in the 2010 Generation Expansion Plan. In both cases, investments are scheduled accordingly, depending on the construction time associated with each technology. Finally, the long-term 2025-2030 time window will correspond to the final 2030 state of the Jamaican electricity system as calculated in this study. Again, start of production is scheduled in 2026 for both new renewable energy plants and the Duncan coal unit, as specified in the 2010 Generation Expansion Plan for the latter case. The planning of investment is defined accordingly.

VII.2.1.b Important assumptions

VII.2.1.b (i) Generation

<u>New capacities:</u>

The same assumptions as in LCOE calculation are made regarding the new generation capacities, whether renewable or conventional, planned to be built during the modelling period (2013-2030).

The same goes for the construction times, with the notable exception of the first conventional power plants, expected to be brought on line within the very next few years, namely the CCGT units in Old Harbour and the coal unit un Hunts bay, for which an accelerated investment period is considered.

Technology	Fuel type	CAPEX	Fixed OPEX (US$/kW-year)	Variable OPEX (US$ /MWh)	Efficiency	Fuel consumption (g/kWh)	Carbon Emission Factor tCO2/MWh
CCGT	ADO	1 317	12,84	2,53	47%	183	0,69
Coal unit	Coal	3 019	28,80	5,00	37%	332	0,92
Combustion turbine	ADO	870	12,48	3,70	34%	254	0,69
Hydro (run-of-river)	-	3 500	50,00	0,00	-	-	0
Hydro (dam)	-	3 500	45,00	0,00	-	-	0
Wind (short-term)	-	2 080	0,00	10,00	-	-	0
Wind (medium-term)	-	1 826	0,00	10,00	-	-	0
Wind (long-term)	-	1 699	0,00	10,00	-	-	0
Solar (short-term)	-	2 689	6,50	0,00	-	-	0
Solar (medium-term)	-	2 096	6,50	0,00	-	-	0
Solar (long-term)	-	1 505	6,50	0,00	-	-	0
Biomass	Biomass	3 000	120,00	4,25	23%	-	0
Waste-to-energy (short-term)	Waste	5 900	333,00	27,00	-	-	0
Waste-to-energy (medium-term)	Waste	5 251	333,00	27,00	-	-	0

Existing power plants:

For power plants already in existence in 2013, calculations rely on the data either provided by JPSCO during the data collection phase as well as those available within the 2010 Generation Plan. For missing data, reasonable numbers are used, based on analogy with similar Jamaican installations for which the data are available or based on the consultant expertise.

Unit Name	Fuel type	Unit size (kW)	Fuel consumption (g/kWh)	CO2 emission factor (tCo2/MWh)	Fixed O&M (US$/kW-year)	Fixed O&M (US$/year)	Variable O&M (US$ /MWh)
Old Harbour							
OH1	HFO	30 000	285	0,67	23,02	690 600	2,33
OH2	HFO	60 000	305	0,67	23,02	1 381 200	2,61
OH3	HFO	65 000	278	0,67	23,02	1 496 300	1,84
OH4	HFO	68 500	273	0,67	23,02	1 576 870	2,54
JEP 1	HFO	74 000	200	0,67	18,46	1 366 040	21,8
JEP 2	HFO	50 000	200	0,67	18,46	923 000	21,8
Hunts Bay							
B6	HFO	65 000	269	0,67	25,19	1 637 350	2,07
WKGN	HFO	60 000	200	0,67	18,46	1107600	21,8
Rockfort							
RF1&2	HFO	36 000	200	0,67	54,57	1 964 520	12,91
JPPC	HFO	60 000	200	0,67	28,63	1 717 800	5,1
Bogue							
6 CT	ADO	115 000	385	0,69	13,1	1 506 500	21,39
CCGT Bogue	ADO	114 000	313	0,69	13,1	1 493 400	3,8
Halse Hall							
Jamalco	HFO	6 000	200	0,67	15	90 000	13,5
Spring Village							
Jamaica Boilers	HFO	1 700	200	0,67	18,46	31 382	21,8
Hydro							
MAGGOTTY	N/A	6 000	N/A	0	35,81	214 860	2,97
L/WHITE RIVER	N/A	4 750	N/A	0	35,81	170 098	3,34
U/WHITE RIVER	N/A	3 200	N/A	0	35,81	114 592	3,32
ROARING RIVER	N/A	4 050	N/A	0	35,81	145 031	1,69
RIO BUENO	N/A	2 500	N/A	0	35,81	89 525	8,99
C/SPRING	N/A	770	N/A	0	35,81	27 574	12,27
RAMS HORN	N/A	450	N/A	0	35,81	16 115	12,27
Wind							
Wigton	N/A	38 000	N/A	0	0	0	113,8
Munro Wind	N/A	3 000	N/A	0	0	0	34

VII.2.1.b (ii) Network reinforcements

The costs assumptions are presented in the table. They are net of the 21.5% duty on material cots, normally applied to such projects.

	CAPEX (US$)
+ 32R Port Antonio Capacitor Bank	576 628
+ 33 Roaring River Capacitor Bank A16	706 169
+ 34 Maggotty Capacitor Bank	900 219
+ 29 69 kV Line Winchester To Port Antonio	6 348 617
+ 30 69 kV Line Winchester To Lyssons	4 891 829
+ 31 Winchester 50 MW Sub & PA Extension	5 669 465
+ 35 Lyssons Substation Extension	762 288

Network investments are assumed to take place during the second modeling period, between 2016 and 2025.

VII.2.1.c Fuel cost scenarios

Contrary to LCOE calculations, fuel costs are not assumed constant through the modelling period. Three different fuels are used in the two scenarios, as represented in the following tables: ADO, HFO and coal. For each of those, three cost scenarios will be assessed: low, medium and high-case.

	Low			Medium			High		
	HFO (US$/BBL)	ADO (US$/BBL)	Coal (US$/ton)	HFO (US$/BBL)	ADO (US$/BBL)	Coal (US$/ton)	HFO (US$/BBL)	ADO (US$/BBL)	Coal (US$/ton)
2013	86	102	90	86	102	90	86	102	90
2014	86	102	90	87	104	92	89	105	95
2015	86	102	90	89	105	95	91	108	99
2016	86	102	90	90	107	97	94	111	104
2017	86	102	90	91	108	99	97	115	109
2018	86	102	90	93	110	102	100	118	115
2019	86	102	90	94	112	104	103	122	121
2020	86	102	90	95	113	107	106	125	127
2021	86	102	90	97	115	110	109	129	133
2022	86	102	90	98	117	112	112	133	140
2023	86	102	90	100	118	115	116	137	147
2024	86	102	90	101	120	118	119	141	154
2025	86	102	90	103	122	121	123	145	162
2026	86	102	90	104	124	124	126	150	170
2027	86	102	90	106	126	127	130	154	178
2028	86	102	90	108	128	130	134	159	187
2029	86	102	90	109	129	134	138	164	196
2030	86	102	90	111	131	137	142	169	206

Table VII-1: Fuel cost scenarios (source: Hinicio)

VII.2.2. Results of economic calculation

Assuming a medium price scenario for all fuels (HFO, ADO and coal) and no carbon price, the total discounted cost of the business-as-usual scenario is around US$7.8 billion, to be compared to US$ 8.37 billion for the 30% renewable scenario:

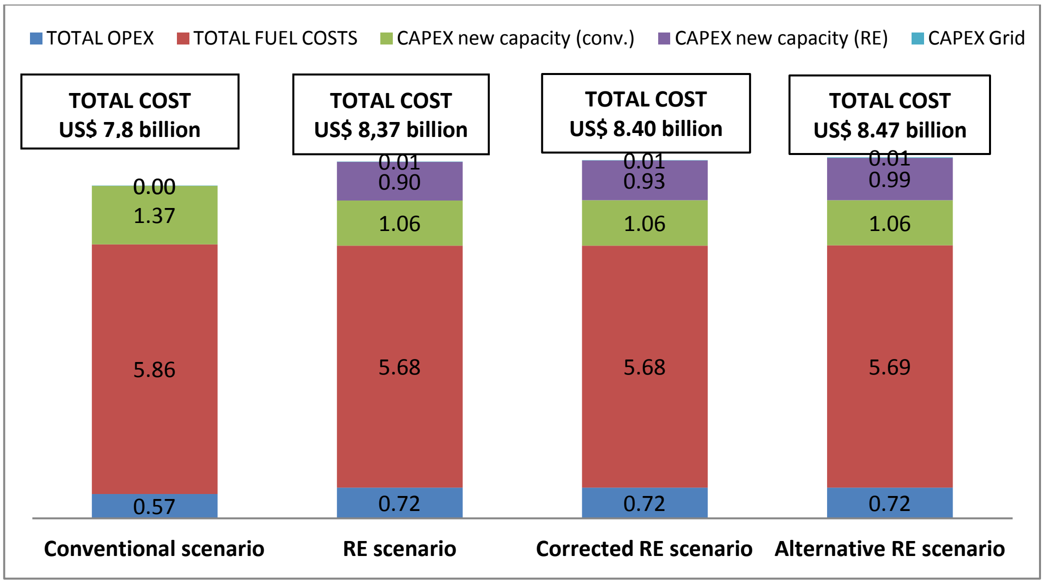


Figure VII-10 - Total discounted costs of the 4 scenarios (medium-price assumption for all fuels) – Source: Hinicio

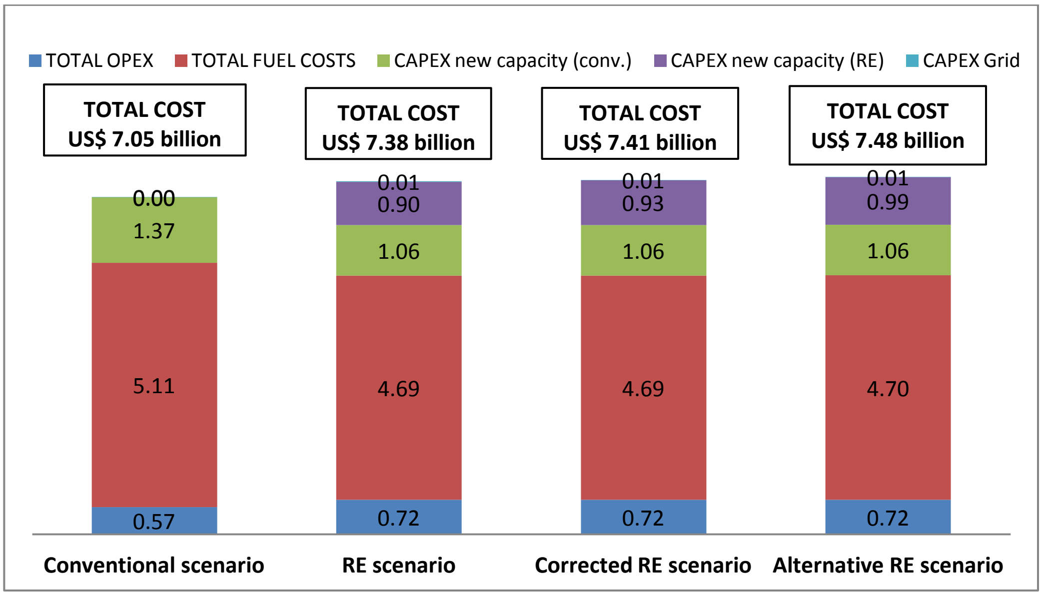


Figure VII-11: Total discounted costs of the 4 scenarios (medium-price assumption for all fuels), with Old Harbour CCGT running on LNG – Source: Hinicio

It appears that the different versions of the renewable scenario give almost identical economic results. For this reason, they will not be differentiated in the analysis below.

The impact of having the Old Harbour CCGT running on LNG is also very significant, inducing a reduction in costs ranging from seven hundred and fifty (750) millions (conventional scenario) to one (1) billion US$ (Renewable scenarios).

In both cases, fuel expenses largely dominate the overall picture, as shown on the detailed breakdowns below. They represent between 64% and 74% of the total costs. As a direct consequence, one can safely state that the price of fossil energies will be the defining factor of the electricity price in Jamaica until at least 2030, even in the most optimistic renewable energy scenario. In addition, faster-than-expected drops in the investment costs of renewables would only have a limited impact on the total electricity costs during that period.

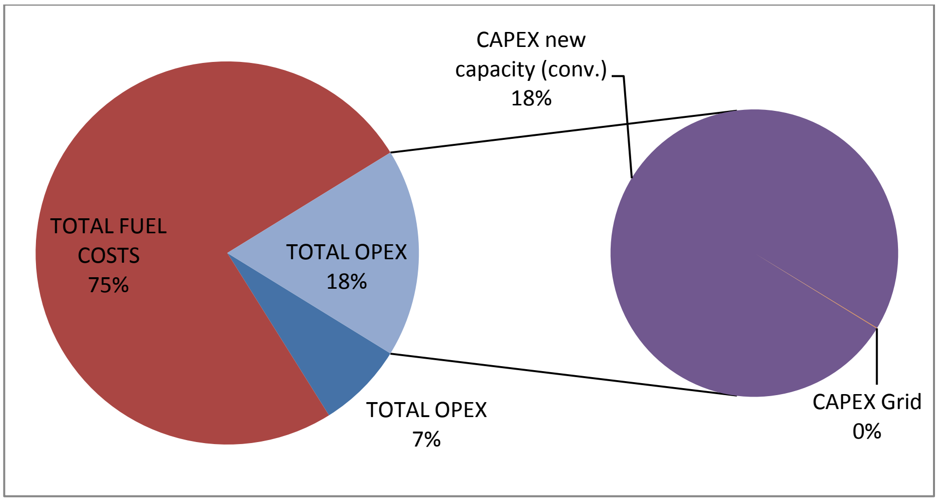


Figure VII-12 - Cost breakdown of the conventional scenario (medium-price assumption for all fuels) – Source: Hinicio

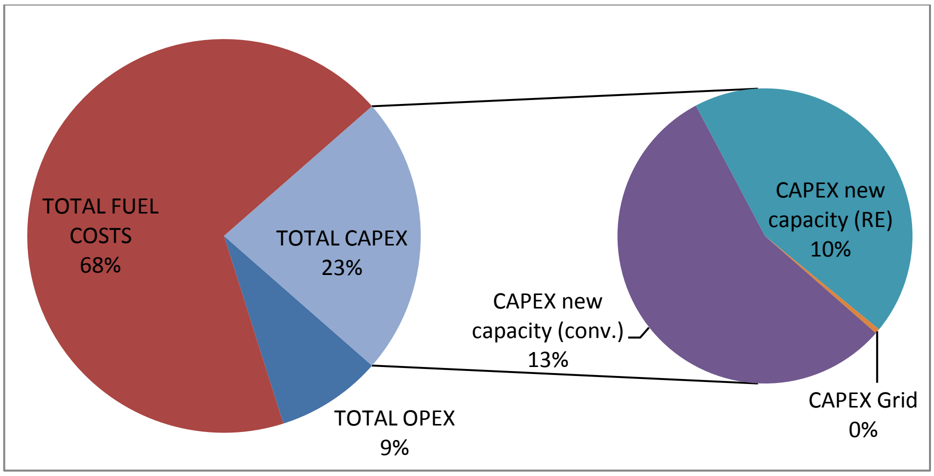


Figure VII-13 - Detailed cost breakdown of the base case renewable energy scenario (medium price assumption for all fuels) - source: Hinicio

In both scenarios, the network component represent a very small part of the total cost: 0.01% in the conventional scenario (less than US$1 million) and 0.15% in the renewable scenario (US$12.6 million), and respectively 0.07% and 0.66% when measured only against the total CAPEX, thus reflecting the technical diagnosis made regarding the robustness of the Jamaican grid.

VII.2.3. Sensitivity analysis

A sensitivity analysis has been performed by Hinicio's team. The overall costs of both scenarios have been calculated for a range of oil and coal price scenarios. ADO and HFO are both petroleum products, one can reasonably assume that their respective prices are highly correlated. Therefore the low, medium and high oil-price scenarios correspond to situations where both ADO and HFO prices are respectively low, medium and high.

The results of the sensitivity analysis, expressed in US$ billion, are presented below for the conventional scenario (table 2), the renewable energy scenario (table 3) and the extra cost of renewables (i.e., the difference between both scenarios, table 4):

US$ billion		Oil prices		
Coal prices		**Low**	**Medium**	**High**
	Low	7,30	7,68	8,12
	Medium	7,40	7,80	8,23
	High	7,54	7,92	8,36

Table 1 - Sensitivity analysis: total cost of the conventional scenario with no carbon price (source: Hinicio)

US$ billion		Oil prices		
Coal prices		**Low**	**Medium**	**High**
	Low	7,86	8,24	8,68
	Medium	7,92	8,30	8,74
	High	7,99	8,38	8,81

Table 2 - Sensitivity analysis: total cost of the renewable scenario with no carbon price (source: Hinicio)

US$ billion		Oil prices		
Coal prices		**Low**	**Medium**	**High**
	Low	0,56	0,56	0,56
	Medium	0,52	0,51	0,51
	High	0,45	0,46	0,45

Table 3 - Sensitivity analysis: cost difference between the two scenarios (source: Hinicio)

In all cases, the renewable energy scenario appears slightly more costly than the conventional one. The total discounted cost of the conventional scenario oscillates between US$7.30 and 8.36 billion, while that of the renewable scenario varies between US$7.86 and 8.81 billion. In other word the cost difference between the two, i.e. the extra cost of the renewable energy scenario under our assumptions, stays in the range of US$0.45 – 0.56 million or about 6 % irrespective of the fuel price scenario used as an input.

VII.2.3.a Fuel consumption

The consumptions of HFO, ADO and coal, as well as associated expenses, have been calculated for the two scenarios.

	Conventional scenario	Renewable energy scenario	Difference (quantity)	Difference (discounted cost)
Total ADO consumption 2013 – 2030 (million BBL)	75.4	76.5	+ 1.1 (+1.5%)	+ US$46 – 53 million
Total HFO consumption 2013 – 2030 (million BBL)	23.5	22.2	- 1.3 (-5%)	- US$46 – 57 million
Total coal consumption 2013 – 2030 (million tons)	13.9	8.0	- 5.9 (-42%)	- US$122.1 – 229.4 million

As reflected on the above table, renewable energies displace coal consumption and reduce it by 4.8 million tons or 42% over the entire modelling period, representing a total discounted cost saving between US$ 122 and US$174 million depending on the coal price scenario. Meanwhile, ADO and HFO consumption vary in opposite directions by the same order of magnitude. They are respectively 1.5% higher and 1.3% lower in the renewable energy scenario compared to the conventional scenario, resulting in a globally comparable consumption of petroleum products in both scenarios. That is reflected in the related fuel expenses, as the cost variations of ADO and HFO roughly cancel each other out, meaning that the costs of importing petroleum product remains more or less constant in both scenarios.

VII.2.1. Levelized cost of new production capacities

The overall levelized cost of new generating capacities has been calculated for both scenarios, with a detailed breakdown between new conventional plants and new renewable plants in the case of the renewable energy scenario. The idea was to gain a better understanding of the reasons for the cost differences highlighted in section VII.2.2.

Obviously, the lifetime of all new production plant goes well beyond the time horizon used in this study, therefore the timeline had to be extended through 2065, which corresponds to Mahogany Vale's 50MW hydropower plant's end-of-life. All costs (including fuel expenses) after 2030 have been assumed constant and equal to their values in 2030. It has been considered that each individual power plant keeps running until the end of its normal lifetime and that all associated costs drop to zero right after that date.

The results of the LCOE calculations are represented on the following graph.

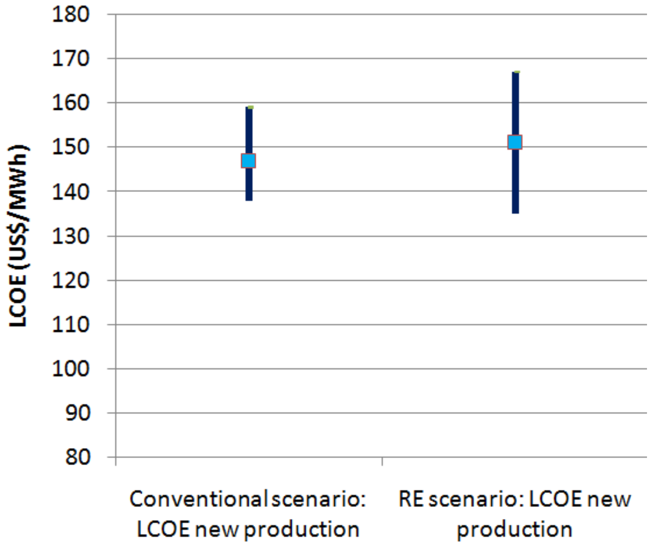


Figure VII-14 - LCOE of new production capacities in both scenarios (source: HINICIO)

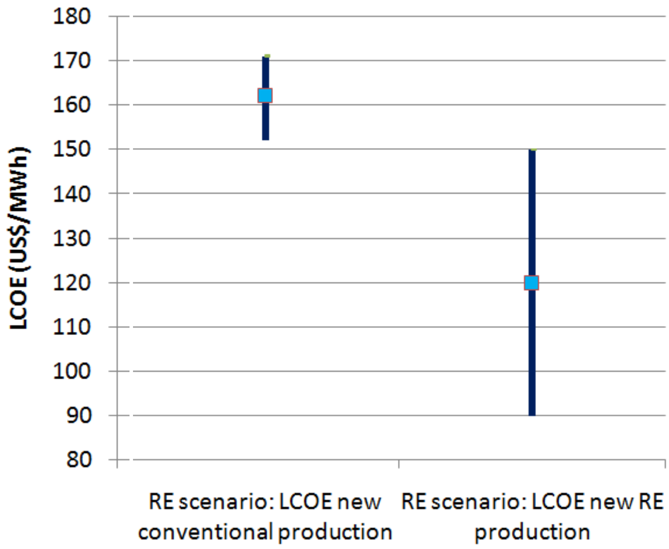


Figure VII-15 - LCOE breakdown of the Renewable Scenario (source: HINICIO)

On the first figure, the reader can find, respectively the LCOE associated with new (conventional) capacities added between 2013 and 2030 in the conventional and renewable energy scenario. The latter is broken down into the LCOE of new conventional plants and the LCOE of new renewable energy plant, which are the two readings on the right side of the chart.

The ranges reflect the uncertainty regarding fuel prices (for conventional plants) and renewable energy technology investment costs.

VIII. CONCLUSIONS

This study was the first study undertaken by the MSTEM concerning the impacts of integrating large amounts of renewable energies into the Jamaica electricity network. The final objective of this study was to assess the cost impacts of renewable energy both in terms of grid reinforcements necessary to maintain safe operation, as well as on the levelized costs of electricity (LCOE) within the Jamaican electricity mix. Regarding these objectives, the consultant draws from its study two main conclusions.

First, renewable energy sources will not have any significant impact on the overall electricity costs between now and 2030. Because of the widespread distribution and location of renewable energy projects, the renewable energy scenario brings generation closer to demand. As a result, renewables allow reduction of power flows through the grid, and consequently reduction of both losses and voltage drops. Renewables could also improve voltage management across the grid if appropriate requirements are introduced into the grid code to take advantage of the capacity induced by power electronics.

Second, economic calculations have shown that the total cost across the entire electricity sector (at the production and transmission levels), over the period 2013-2030, are slightly higher in the renewable scenario. The cost difference between the conventional and the renewable scenarios is in the range of 500 million US$ (irrespective of the assumptions made regarding the costs of fuels) for a total estimated cost amounting to more than 8,000 million US$. However, based on LCOE calculations, it is of crucial importance to note that the higher cost of the renewable scenario is primarily due to the high LCOE of the newly added conventional plants running on ADO rather than to the costs of renewables themselves, which are generally more competitive than ADO-based power plants.

From a technical point of view, one can safely state that the integration of 30% renewable will be cost-neutral at the transmission grid level. However, Variable Renewable Energy (VRE) sources can have significant impacts on the dynamics of the system, as described in section 6. On the one hand, these impacts should not be underestimated, as they could put the operation of the system at risk if they were insufficiently anticipated. However on the other hand, these impacts should not be overestimated, because an overly conservative approach would lead to a waste of valuable natural resources of the country. Impacts on electrical systems dynamics are one of the most investigated topics in today's electrical science and engineering. Any potential hurdle has technical solutions. These solutions always come with an associated cost and their implementation should be carefully justified and documented by relevant studies, and eventually decided upon based on solid arguments. In the case of Jamaica, the instantaneous penetration of Variable Renewable Energy sources (wind and solar PV) exceeds 30% in a in a minority of cases, which is generally considered as a safe limit in islanded networks.

From an economic point of view, it is important that the noted cost difference between the two scenarios roughly falls within the uncertainty margin. The study was mainly based on the 2010 Generation Expansion Plan results and assumptions. The consultant has of course adjusted the conventional portfolio downwards to account for the introduction of renewables and avoid unrealistic results in the network study. The consultant has not questioned sizing, fuel type, technologies and planned commissioning dates for the units scheduled in the 2010 Generation Plan. Changes in these assumptions, as well as in capacity and efficiency factors, can lead to significant variations in the economic results.

In the consultant's opinion, MSTEM should urgently update the 2010 Generation Expansion Plan, which is becoming obsolete with the introduction of renewables. At the same time, a Smart Grid Roadmap including the findings of an updated generation expansion plan will open the way for the solution of all remaining questions concerning the integration of renewables at a large scale in Jamaica by assessing and increasing the flexibility in the power system.

Under all scenarios, electricity costs are likely to be on the rise over the next decades due to external factors, chiefly fossil fuel prices. This study has highlighted two possible pathways for Jamaica to mitigate those cost increases. On the one hand, coal will probably turn out to be the cheapest option within the realm of conventional solutions. Still, this technology might very well be confronted to key practical roadblocks resulting in higher costs than expected, primarily the need to build dedicated facilities from scratch, including a harbour, fuel treatment and storage units, etc. The efficiency of coal units should also be considered bearing in mind that the assumptions made in the 2010 Generation Plan are probably optimistic.

On the other hand, LCOE calculations showed that renewables are generally cheaper than conventional power plants in the Jamaican context (except coal). They even have significant advantages over coal in terms of security of energy supply and uncertainty regarding fuel prices. For those reasons, increasing renewable beyond the 30% limit could also be viewed as a way to ensure a competitive electricity price in Jamaica in the long-term. In this regard again, smart grid technologies like energy storage, including pumped-hydro and batteries, could be assessed as a long-term enabler to integrate a high amount of renewables into a generation expansion plan in an islanded network.

Finally, from a network operation and planning point of view, the consultant recommends the possibility for synchronous units being operated, even slightly, in under excited mode to be considered in the future. This would help voltage management and have a negligible impact on equipment service life. This could be done through appropriate requirements at the delivering point for generating units in the grid code.

The present report is the final report of this study and concludes the consultant's assignment.

IX. APPENDIX 1 - PROBABILITY DISTRIBUTIONS AND MODELS USED

IX.1. THE LOAD

The probability of load consumption has been extrapolated from the data given to the consultant of the load measured from January 1st, 2012 to December 31st, 2012, with a 15 minutes time step.

The representation of these data is given below:

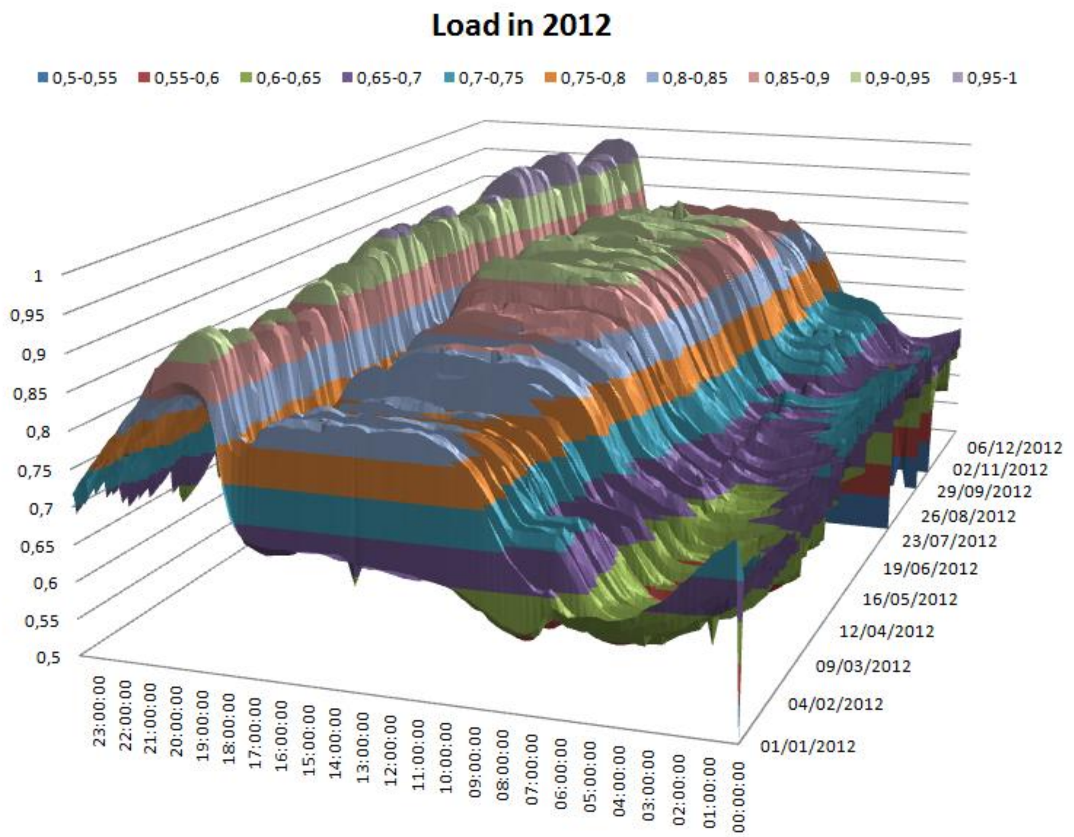


Figure IX-1: Value of the load (pu) according to day and hour in the day

These data can then be translated into probabilistic terms in order to know to probability of occurrence of each value of the load.

This gives the following results, for both the probability distribution function and the cumulative distribution function:

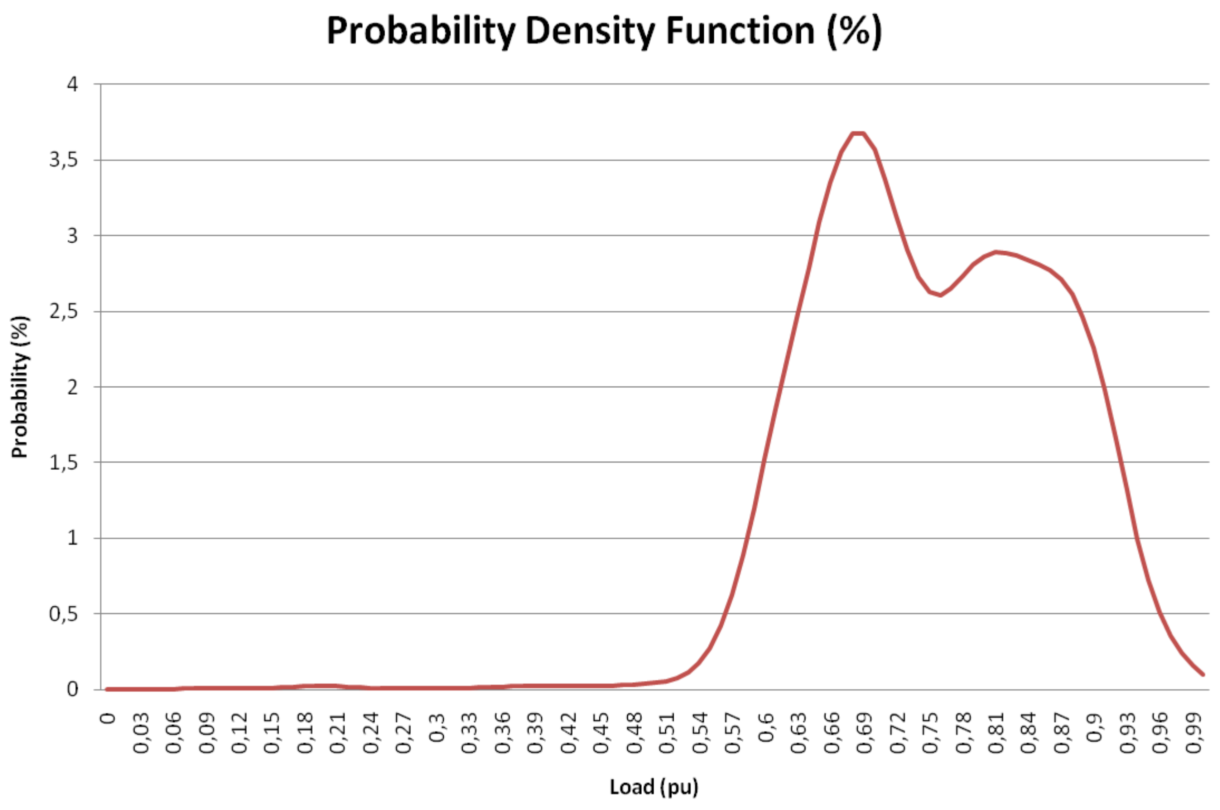


Figure IX-2: Probability Density Function of the load

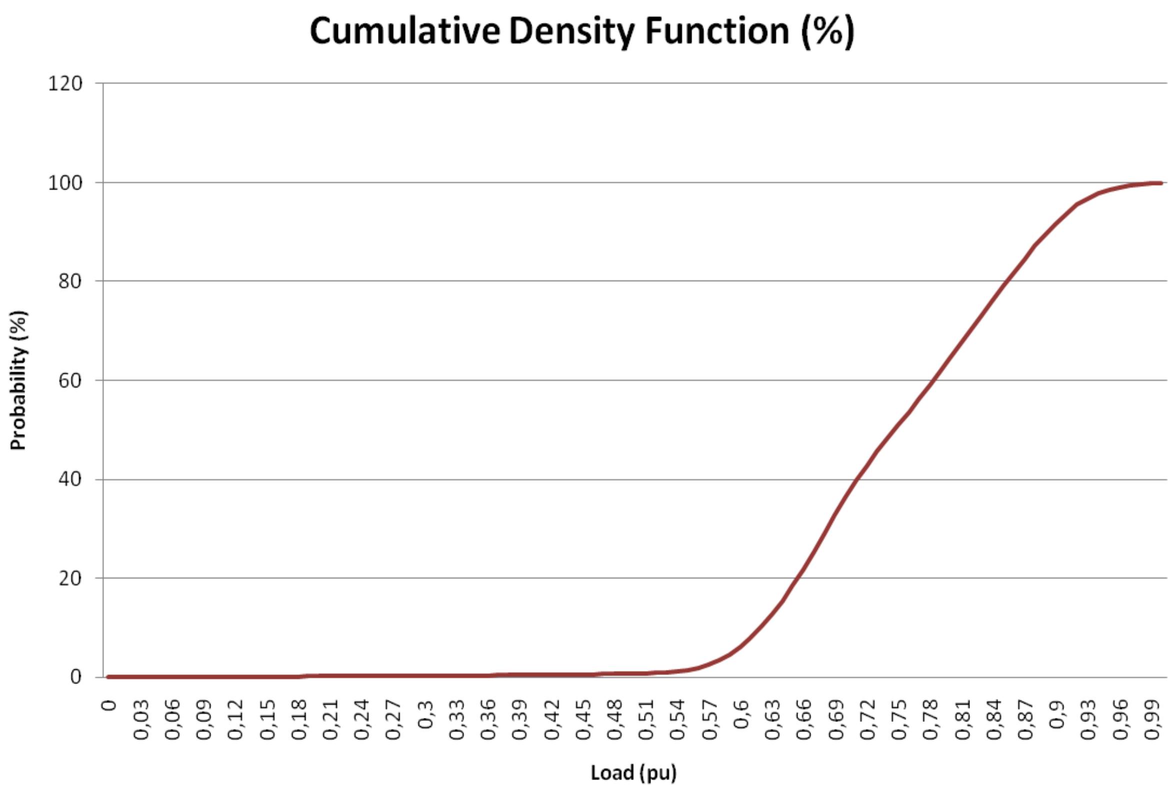
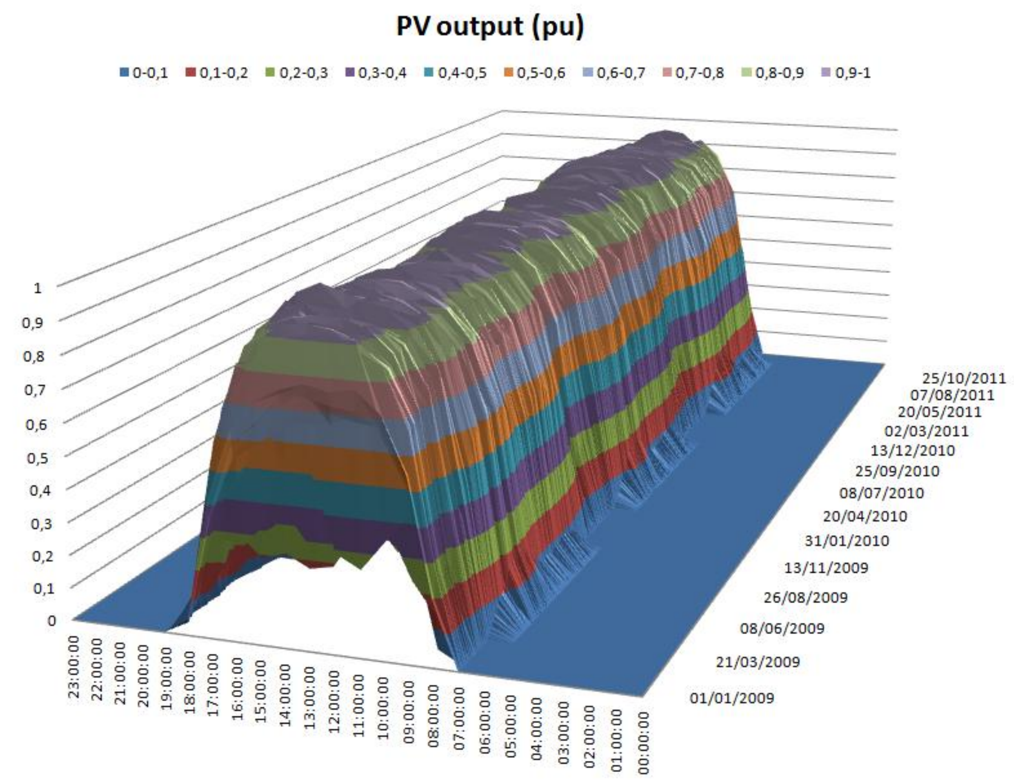


Figure IX-3: Cumulative Density Function of the load

IX.2. PV OUTPUT

PV output was estimated from data available from December the 31st, 1996 at 20:00 until June the 30th, 2012 at 13:00.

In order to limit the complexity of the model without impairing the representativeness of it, it was decided to keep only the data of the years 2009, 2010 and 2011.



These data can then be translated into probabilistic terms in order to know to probability of occurrence of each value of the load.

Since the PV output only takes values during days, it was decided to separate the study between the day (from 8 o'clock to 18 o'clock) and the night (the rest of the day).

This separation gives the following results, during the day, for both the probability distribution function and the cumulative distribution function:

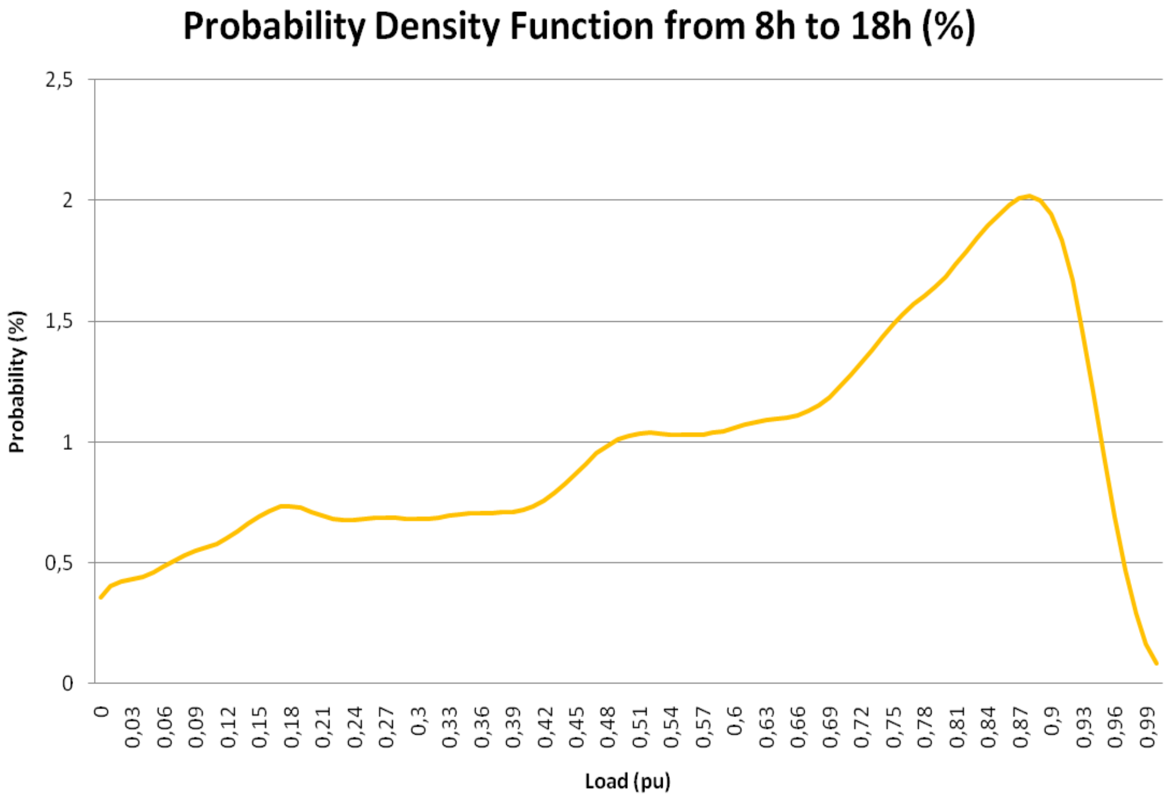


Figure IX-4: Probability Density Function of the PV output during day

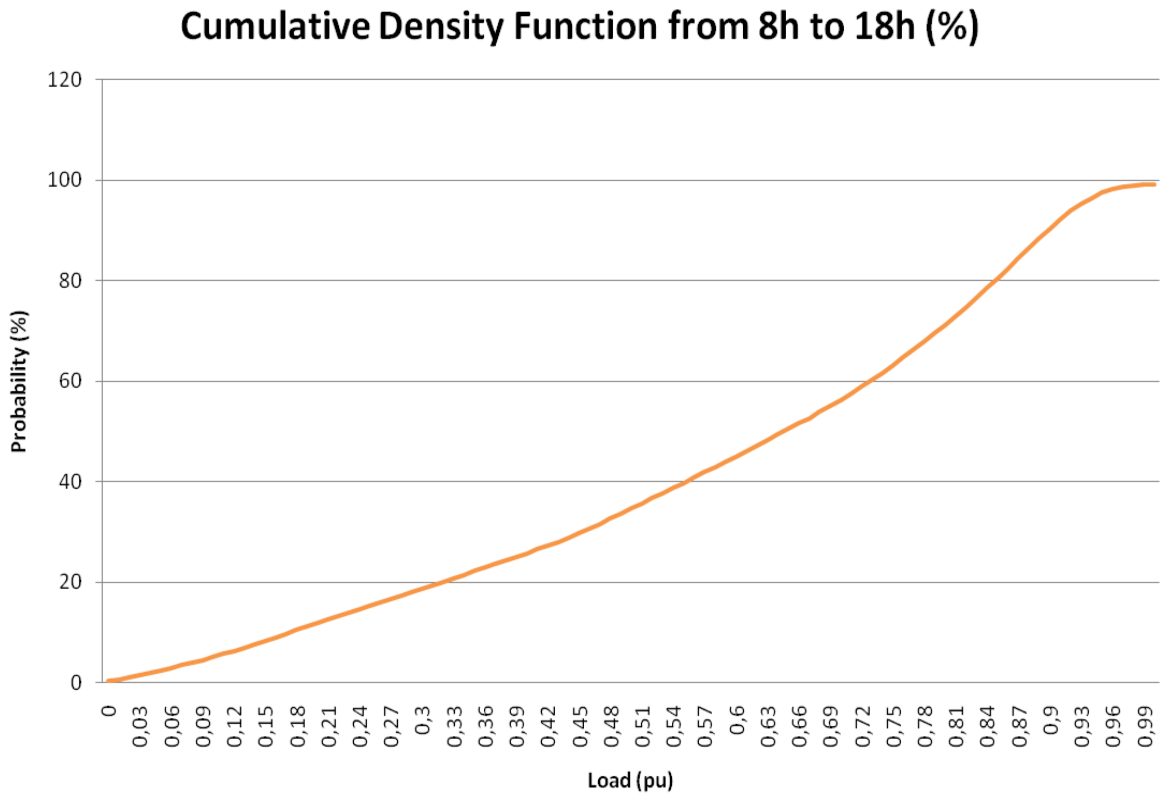


Figure IX-5: Cumulative Density Function of the PV output during day

IX.3. WIND LAWS

As explained in the section “Construction of Renewable energy portfolios – Wind”, two wind regimes have been selected for this study, based on reports [7] and [8].

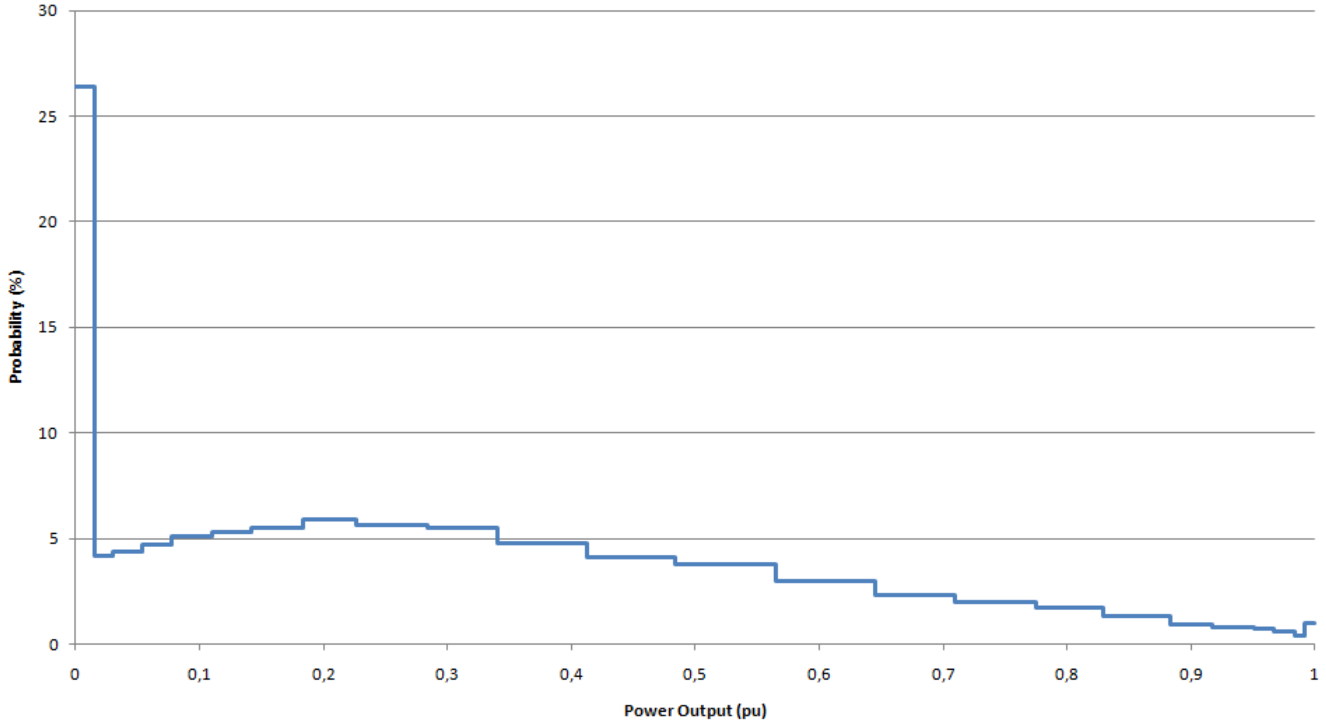


Figure IX-6: Probability of occurrence of power output, wind regime #1

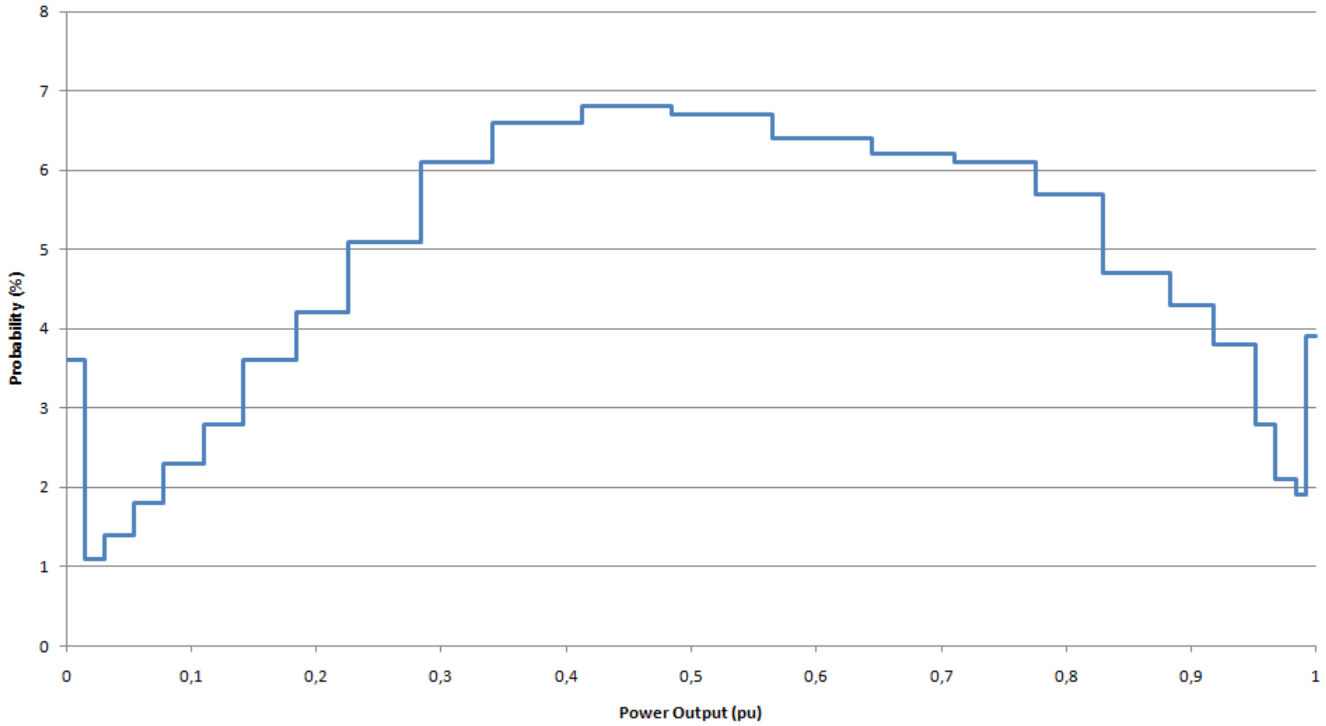


Figure IX-7: Probability of occurrence of power output, wind regime #2

X. APPENDIX 2 - NUMERICAL LIMITS

For information, the following tables give the percentages of times the simulation could not converge because of numerical limits:

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.2 %	0.8 %	0.0 %
"N-1" network (10,000 simulations)	0.60 %	0.83 %	0.52 %

Tableau X-1: Numerical limits – 2030 Conventional Plants scenario

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.8 %	1.2 %	0.3 %
"N-1" network (10,000 simulations)	1.12 %	1.99 %	2.46 %

Tableau X-2: Numerical limits – 2030 With Renewable scenario, day

	High Flow	Intermediate Flow	Low Flow
"N" network (1000 simulations)	0.8 %	0.9 %	0.2 %
"N-1" network (10,000 simulations)	0.51 %	0.80 %	0.68 %

Tableau X-3: Numerical limits – 2030 With Renewable scenario, night

Non-convergence of the OPF can be due to various factors, including mathematical convergence of the optimization problem. In addition, optimization processes can be strongly dependant to the starting point. In his methodology, the consultant uses the OPF to solve a large range of mathematical problems, with a unique starting point for each series of simulations, causing probably part of these non-convergences.

Non-convergence is a common issue in optimization problems, but it remains important to analyze it. The following tables show the density functions of wind and solar power among not converged cases in Renewable scenario, Low Flow Day.

Each of these 3 density functions is very similar to its corresponding density function set in input of the optimization problem: VRE are not over represented in not converged cases and do not seem to be a specific cause of non-convergence. Another way to put it is that correlations between the density functions in converged cases and in not converged cases are very high (above 80% for PV and 90% for the wind). The consultant thus concludes that non-convergence is not significant for the results of this study.

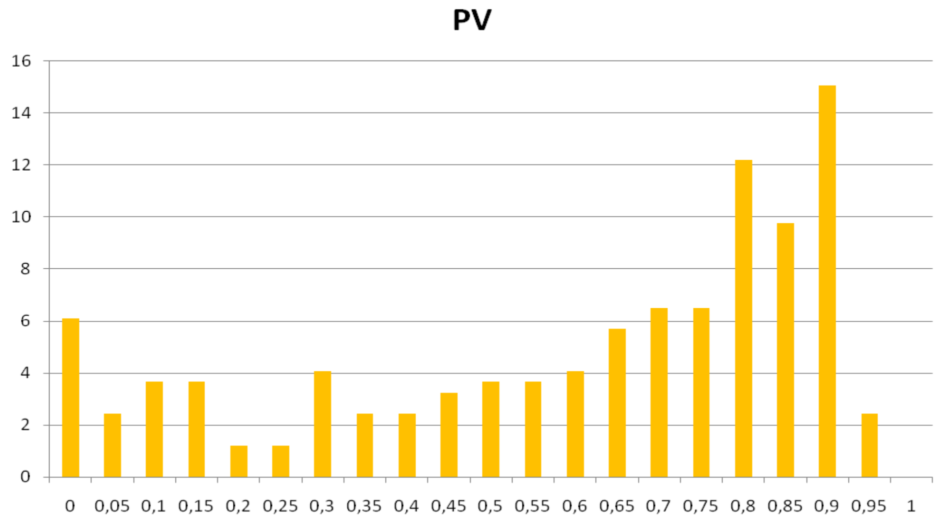


Figure X-1: density function of PV during Low Flow Day season when not converged

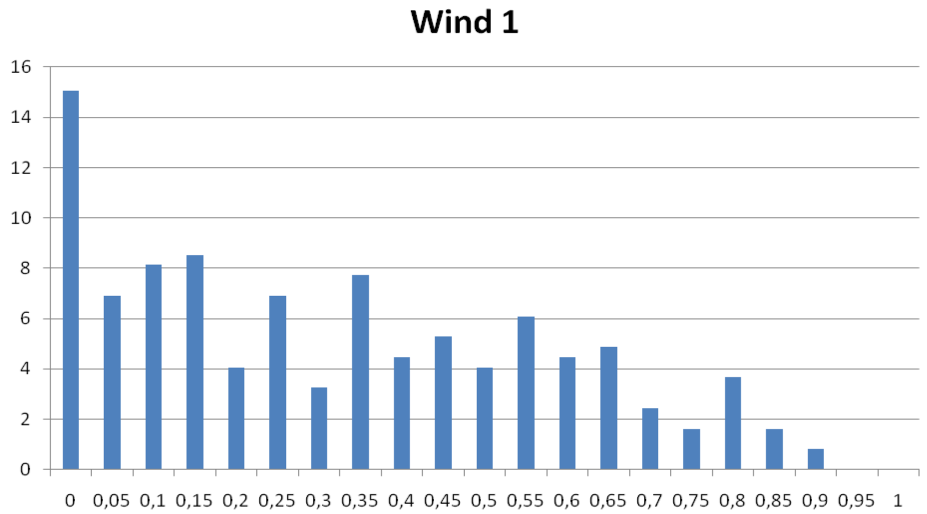


Figure X-2: density function of Wind1 during Low Flow Day season when not converged

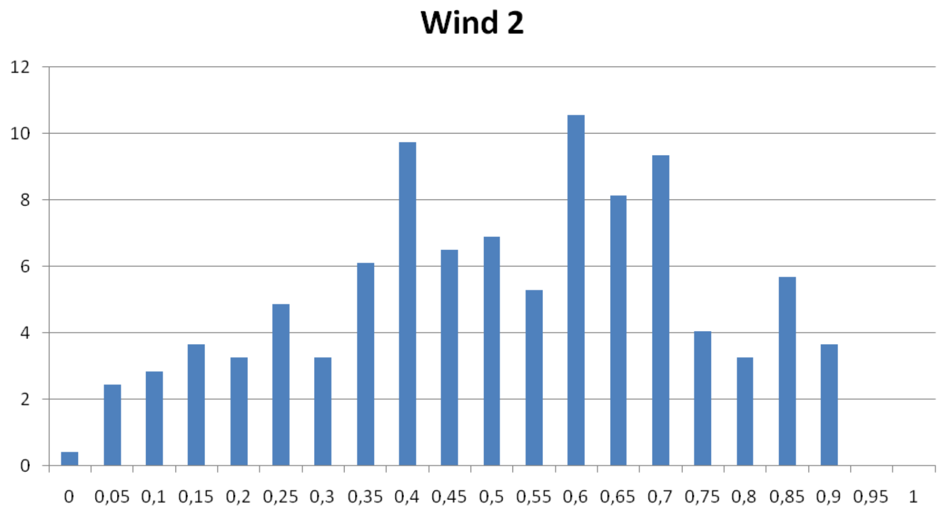


Figure X-3: density function of Wind2 during Low Flow Day season when not converged

X.1. APPENDIX 3 – LOCATION OF THE 2026 114 MW PLAN

This appendix presents the results of simulations conducted in order to locate the last 114MW coal unit, to be commissioned in 2026. No indication was given by the 2010 Generation Plan, thus the consultant has identified three possible locations and has tested them.

The following tables present the voltage constraints generated by putting this 114 MW plant in Rockfort, Bogue or Duncan.

	High Flow	Intermediate Flow	Low Flow
“N” network	1.6%	2.7%	49.8%
“N-1” network	17.98%	17.45%	62.25%

Table X-4: Voltage constraints – 2026 coal unit at Rockfort

	High Flow	Intermediate Flow	Low Flow
“N” network	9.1%	8.6%	13.3%
“N-1” network	24.2%	22.5%	35.0%

Table X-5: Voltage constraints – 2026 coal unit at Bogue

	High Flow	Intermediate Flow	Low Flow
“N” network	2.9 %	2.5 %	5.7 %
“N-1” network	23.74 %	22.67 %	33.35 %

Table X-6: Voltage constraints – 2026 coal unit at Duncan

From these results, the consultant has decided to add the 114MW coal unit in Duncan. Remaining constraints are then treated in section 5.

XI. APPENDIX 4 – REFERENCES

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