DEFINING REASONABLE PV PENETRATION GOALS:

ASSESSMENT OF THE EFFECT OF HIGH PV CAPACITY LEVELS ON LOW VOLTAGE NETWORKS

M. Weissenbacher, N. Micallef
Institute for Sustainable Energy
University of Malta

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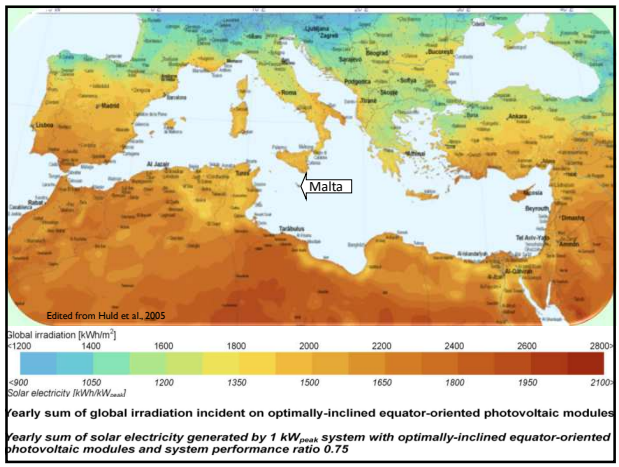


Yearly sum of global irradiation incident on optimally-inclined equator-oriented photovoltaic modules

Yearly sum of solar electricity generated by 1 kW_{peak} system with optimally-inclined equator-oriented photovoltaic modules and system performance ratio 0.75

Malta: 316 km² ; 417,608 inhabitants

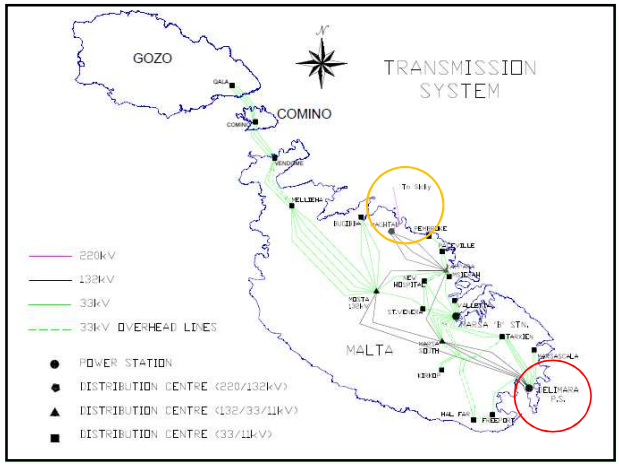
Gozo:
67 km², 37,000 inhabitants

Power Sector

- Demand: ca. 2.1 TWh
- Peak load: 438 MW (July 2015)
- Total current generation capacity: 490 MW
- 200 MW (220 kV) HVAC interconnector to Sicily
- 215 MW CCGT plant *under construction* (LNG)

Network Level	Nominal Voltage (3-φ)	Steady-state	Voltage Range
LV	400V	± 10%	360V – 440V (3-φ) 208V – 254V (1-φ)
MV	11kV	± 5%	10.45kV – 11.55kV (3-φ)
MV	33kV	+ 5% , -10%	29.70kV – 34.65kV (3-φ)
HV	132kV	± 6%	124.08kV – 139.92kV (3-φ)

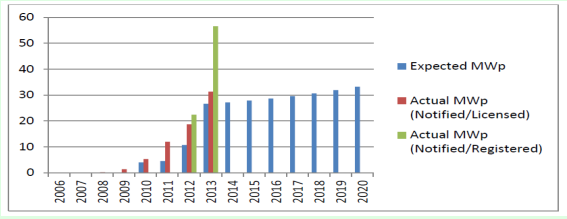
- Grid code: European Standard EN 50160:2010
- 132kV HV circuit (tunnels) from Delimara to distribution centers (Marsa, Mosta, Kappara): 132kV to 33kV or 11kV
- Continues to Maghtab Terminal Station, where the interconnector arrives (220kV to 132kV)
- 33kV circuit connects to 18 distribution centres: 33kV to 11kV (OLTC, SCADA)
- 11kV circuit connects to 1,200 sub-stations: 11kV to 400V/230V
- Gozo: one 33kV/11kW center, 140 sub-stations



Malta Renewable Energy Action Plan

Renewable Energy Option	%	GWh/year
~~Offshore~~ wind	3.48	216
Biofuels	2.40	149
Energy from waste –Electricity	2.18	135
Solar PV	0.69	43
~~Onshore~~ wind	0.61	38
Solar Water Heating	0.52	32
Energy from waste – Heat	0.32	20
TOTAL:	**10.20**	**634**

Photovoltaic Capacity



End-2010: 745 kWp connected to the grid,
End-2014: 53,538 kWp connected to the grid, another 25,887kWp registered.

Residential PV systems end-2014:
63% of connected capacity, 95+% of installations.

Photovoltaic Capacity

- Large PV installations require a grid integration study
  - associated integration costs such as transformer upgrades borne by the PV investor.
- Photovoltaic installations up to 16 Amps on any of the electrical A.C. phases (230/400V) do not require an authorization or license in Malta.

Model: data

- 33 million residential Smart Meter 15-minute records for electricity consumption and photovoltaic electricity generation
  - 4 substations known to require seasonal substation transformer tapping adjustments in order to avoid overvoltage issues
  - 1,600 consumer meters, 157 PV meters
  - Residential meters do not register reactive power
  - Plus 200 PV meters (randomly selected)
  - 01/01/2013 to 30/06/2014
- Sub-station master meters

Model

- Structured Query Language (SQL) model
  - Four substations
  - Filtering routines
  - 15-min data converted into hourly periods for each type of consumer meter
  - combined with generic PV output profile model
  - compared to substation master meter data sets

Model

- DIgSILENT PowerFactory
  - GIS data, physical network information (transformer/cable characteristics: impedance, distance, etc.)
  - Two substations: monthly average hour records (consumer and PV profiles from the SQL model)
  - One substation: additional model exclusively with original data
  - Entire Gozitan 11kV network with all substations (loads based on connected type and number of consumers)
  - Load flow studies

Photovoltaic penetration scenarios

Tested in DIgSILENT model against EN 50160:2010 "*Voltage Characteristics of Public Distribution Systems*"

- *"No PV"*
- *"Current"* (meters as of 31/12/2014)
- *"+1kWp"* (1kWp PV system added to those households that had no PV systems installed)
- *"+2kWp"* (2kWp PV system added to those households that had no PV systems installed)

Results/Conclusions

- SQL model : close correlation between the sum of individual meters and the associated substation master meters. Instances of reverse power flow during the period April to June around 11:00 to 15:00 at the current PV penetration level for all four modeled substations.
- DIgSilent: Results with actual data and SQL profiles very similar
- *"No PV","Current" : all feeders within* ±10% voltage range
- *"+1kWp" :* phase balancing sufficient

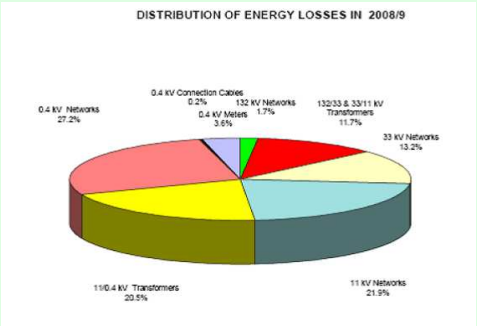
Results/Conclusions

- *"+2kWp" :* transformers had to be replaced to allow for greater tapping flexibility
- One sub-station: OLTC 11kV:400V 9-step tap change transformer was required since two tap changes had to happen during the same day to keep all feeders within limits.
- Other sub-station: switching inverters to reactive power Q(V) control, or else new manual tap changing transformer (from 11kV:433V to 11kV:400V)
- (Solutions with energy storage are not included in this presentation.)

Results/Conclusions

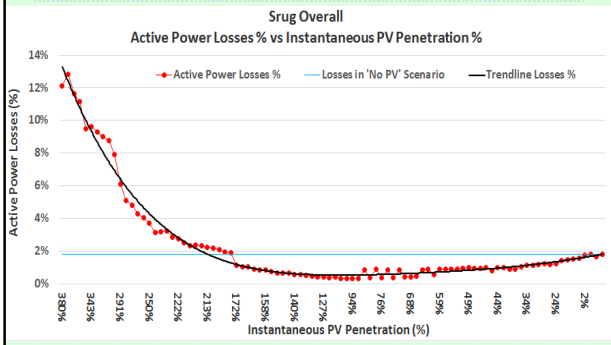
Technical barriers to high PV penetration can be overcome, but at the cost of infrastructure upgrades.

Results/Conclusions: focus on active power losses



Scenario	No PV	Current	+1kW	+2kW
Substation 11kV/433V transf. rating (kVA)	500	500	500	500
Energy consumption, metered (kWh/year)	106,219	106,219	106,219	106,219
Peak load, evening (kW)[1]	41	41	41	41
Peak load, daytime: 11:00-15:00 (kW)[2]	25	25	25	25
Total PV capacity (kWp)	-	26.72	44.72	62.72
Total PV output (kWh/year)[3]	-	41,812	70,771	101,286
Penetration based on (evening) peak load[1]	-	65%	108%	152%
Penetration based on (daytime) peak load[2]	-	107%	179%	251%
Maximum Instantaneous Penetration[4]	-	304%	518%	737%
Penetration based on System Capacity[5]	-	5.3%	8.9%	12.5%
Penetration based on Energy	-	39%	67%	95%
Penetration based on self-consumed Energy	-	31%	36%	40%
Losses, absolute (kWh/year)	1063	982	1258	2040
Losses, relative (percent)	1.00%	0.92%	1.18%	1.92%

Results/Conclusions: focus on active power losses



Thank you!

Noel Micallef
Manfred Weissenbacher

manfred.weissenbacher@um.edu.mt

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