The particularity of the power network incorporating with the aggregation of distributed PV systems

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The particularity of the power network incorporating with the aggregation of distributed PV systems

Part 1:
General Considerations – Particularity of PV

Part 2:
Aggregation of a large number of PV systems

Part 3:
Bulk Systems – LSPV to VLSPV
1. Irregularity:
   - Random fluctuation for seconds, minutes to hours by cloud movement can be equalized over a broader area

2. Regularity:
   - Daily change by earth rotation: day and night can be equalized by east-west inter-tie
   - Seasonal change by orbital motion can be equalized by north-south intertie
   - Limited capacity factor \( < \frac{2800}{8760} \times 100 \% \approx 30 \% \) terrestrially max

3. Universality:
   - almost Everywhere Accessible: peaceful energy
   - terrestrial max: 2800 kWh/m² in Sahara
   - however, rather evenly distributed: e.g., 1400 kWh/m² in Japan; 1200 kWh/m² in Central Europe
NEDO’s City of Ota Project
Residential PV Potential
Central Tokyo (23-Wards)

Residential Roofs - 20%

A Half of Roofs for PV

72% population in Greater Tokyo (8.5 / 11.8 Mln)

PV area = 65.0 km²
PV capacity = 9.7 GW
Annual E. = 10.8 TWh/Y
**PV2030 Roadmap**

- **Cell Tech>>** Cost Reduction by Tech. Generation Change
  - Bulk Si & Thin Film Si/Compound
  - Very-Thin Cell/Multi-junction
  - New Material/Structure Ex: Dye-sensitized

- **System Tech>>** Less-dependent on Grid from Individual to Clustered
  - Battery Backed-up
  - Large System Long Life BOS
  - Active Grid Control
  - New Material Entering

- **Electricity Cost-down**:
  - 2002: ~50 JPY/kWh
  - 2007: 30 JPY/kWh
  - 2010: 23 JPY/kWh
  - 2020: 14 JPY/kWh
  - 2030: 7 JPY/kWh

- **22% η module 50 JPY/W**

- [Link to PV2030 Roadmap](http://www.nedo.go.jp/english/archives/161027/pv2030roadmap.pdf)
Installable PV (GW) up to 2030

2 trillion JPY/Y Market

PV2030 Base Case
10% approx. of Domestic Electricity

Case 1: Business as usual
Case 2: R&D and Market Penetration according PV2030 Base Case
Case 3: Accelerated R&D and Market Penetration with large-scale industrial use
Potential: Physical Limit by residential, public, industrial, unused land, etc.

Cases:
- Case 1: 54 GW
- Case 2: 102 GW
- Case 3: 202 GW
- Potential: 8,000 GW

Breakdown:
- Single Family: 7 JPY/kWh
- Multi-Family: 14 JPY/kWh
- Industrial: 23 JPY/kWh
- Business: 23 JPY/kWh
- Transport: 23 JPY/kWh
- Public: 23 JPY/kWh
- Unused H2, etc.: 23 JPY/kWh
NEDO’s PV Cluster Demonstration Experiment Project in City of Ota

No. of PV Houses: 550
NEDO’s PV Cluster Demonstration Experiment Project in City of Ota

No. of PV Houses: 550
Example: Equalization over Area

"Josai-no-Mori" New Town Ota City

Average

Vertical Axis: Irradiance (kWm⁻²)
Horizontal Axis: Time of day (hour: minute)

≈ 750m
≈ 500m
NEDO’s City of Ota Project

1 PV House

31 July 2007

Equalization

PV output (kW)

Time of day (hour)

516 PV Houses

31 July 2007

PV output (kW)

Time of day (hour)
Equalization – An Example

1 PV House

516 PV Houses

PV output (kW)

Time of day (hour)

PV output (kW)

Time of day (hour)
Fluctuation Energy by Frequency

Power Spectrum

Frequency (Hz)
Fluctuation Energy by Time Period

Power Spectrum

Period (s)

10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Residential Loads

1 PV House

516 PV Houses

Larger Equalization
Expected Equalization for Broader Area

Expected Overall PV Output

METI’s Monitoring Plan

≈200 sites over Japan

Source: Agency of Resources and Energy, METI, 9 Sept. 2008
Regularity - Residential PV Subsidy Program

Average for All Reported Houses

Source: New Energy Foundation

Max (FY2001): 1055 (h)
Min (FY2003): 896 (h)
Average: 980 (h)

FY1997 – 2003

1997 年度
1998 年度
1999 年度
2000 年度
2001 年度
2002 年度
2003 年度
月別平均
全平均

12-15 Jan 2009
Seasonal Regularity - Residential PV Subsidy Program

Average Monthly Yield for All Reported Houses

Legend:
- **Monthly average** for 7 yrs
- **Annual average** for 7 yrs
- **Max (FY2001): 1055 (h)**
- **Min (FY2003): 896 (h)**
- **Average: 980 (h)**

Source: New Energy Foundation
Seasonal Balance between PV and Electricity

Source 1: Typical 5 electricity consumptions by 10 utilities in Japan but 9 in 1975 reported by the Federation of Electric Power Companies of Japan.

Source 2: Kurokawa added PV generation curve coincident to monthly PV yield reported by NEF as on the previous slide.
Daily Power Balance between PV and Electricity

Extreme Case A: 100 GW PV Introduction over Japan

100GW
Clear day profile

10 Utilities in Japan but 9 in 1975
Source: The Federation of Electric Power Companies of Japan + Kurokawa
Daily Power Balance between PV and Electricity

**Extreme Case B:**

- 150 GW PV

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**Source:** The Federation of Electric Power Companies of Japan + Kurokawa

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**10 Utilities in Japan but 9 in 1975**
Daily Power Balance between PV and Electricity

Extreme Case C: 150 GW PV + Storage

Role of Battery Storage

Stable margin for nuclear operation

10 Utilities in Japan but 9 in 1975
Source: The Federation of Electric Power Companies of Japan + Kurokawa
Issues: Massive, Bulky PV Penetration and its Integration to Power Systems

- In spite of large possibility for PVs in kWh, Solar Power Peak in kW tends to become much larger than gross electric power system peak.

- In case of Nuclear Power Station: utilizing Pumping-up Station for adjusting power balance.

- In case of the higher penetration of PV, some energy storage may be introduced. What Kind, Where and How Large?
b: a distributed small battery for each house
Σb: aggregation of distributed small batteries
B: capacity of Battery station
B: capacity of battery station for Bulk PV

Expected: B << Σb

to minimize total cost

to overcome voltage rise by reversal flow
Hourly Irradiation for Average Year

MET-PV2 (Tokyo)
Monthly-Averaged Hourly Domestic Energy Consumption by A Fully Electrified Home

Demand Energy (kWh/h)

Japanese Standard Time (h)

Note: Specified for year around 2030 by Jyukankyo Research Institute Inc.
PV Energy by 18% Efficiency (kW/m²)

Number of Days

SOC (kWh)

Energy (kWh)

Surplus
Shortage

Optimized Storage Capacity

7 kW PV

- supplied by External Utility

20 kWh preferred

Winter

Summer

Battery Capacity (kWh)

1/60 1230 kWh

Ignoring Seasonal Gap

Optimized Storage Capacity

1230 kWh

METPV2 (Tokyo)
Key Innovative Energy Technologies toward "Cool Earth 50"

Efficiency improvement

<table>
<thead>
<tr>
<th>Oil</th>
<th>LNG</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power generation/transmission</td>
<td>Efficient coal-fired power plant</td>
<td>CCS</td>
</tr>
<tr>
<td>Efficient LNG-fired plants</td>
<td>Superconducting power transmission</td>
<td>Innovative Photovoltaics</td>
</tr>
</tbody>
</table>

Low carbon Tech

<table>
<thead>
<tr>
<th>Nuclear Power</th>
<th>Biomass</th>
<th>Solar</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovative Photovoltaics</td>
<td>Advanced nuclear power</td>
<td>Biofuel</td>
<td></td>
</tr>
</tbody>
</table>

Supply side

Transport

- ITS
- FCV
- PHEV/EV

Industry

- Innovative materials/manufacturing process
- Steel-making process with hydrogen

Residence/Building

- Super heat pumps
- Efficient houses/bldgs.
- Efficient lighting
- Low energy IT devices/networks
- Fuel cells for residential use
- HEMS/BEMS/Regional EMS

Cross-sectional

- Power storage
- Power electronics
- Hydrogen production/storage/transport
PV R&D Initiatives toward ‘Cool Earth 50’

- Cool Earth 50
- 3rd Gen
- Innovative PV Cells 2008-2014
- η > 40%

1st Gen
- c-Si
- a-Si
- Sunshine Project
- New SS Project

2nd Gen
- thin-bulk c-Si hybrid TF-Si CIS dye-sensitized polymer
- PV2030
- R&D for Tomorrow

3rd Gen
- ultra high efficiency multi-junction cell quantum nano-structure others innovative
- η > 40%

Electricity Cost Target
- Jpn. Yen/kWh
- 23 JPY/kWh
- 14 JPY/kWh
- 7 JPY/kWh

- wintersun.sourceforge.net
- 30 kurochan

English translation from http://www.iae.or.jp/research/result/ene_map_2008.html
Considerations on storage in Cool Earth 50

### High-Performance Power Storage

<table>
<thead>
<tr>
<th>Year</th>
<th>For Vehicles</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density</td>
<td>70~100 Wh/kg</td>
<td>150 Wh/kg</td>
<td>200 Wh/kg</td>
<td>500 Wh/kg</td>
<td>5,000 JPY/kWh</td>
<td>5,000 JPY/kWh</td>
</tr>
<tr>
<td>Cost</td>
<td>200,000 JPY/kWh</td>
<td>30,000 JPY/kWh</td>
<td>20,000 JPY/kWh</td>
<td>15,000 JPY/kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>For Stationary</td>
<td>10 years</td>
<td>20 years</td>
<td>15,000 JPY/kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Adv. Li-ion
- Batteries with new concept/principle
  - Drastic performance improvement and cost reduction
  - Metal-air battery, etc.

#### Li-metal, Li-S
- For Vehicles
  - Nas battery, Redox flow battery
  - For load leveling, improvement of power quality, load change compensation
  - Ni metal hydride battery
  - Stabilization of wind power/photovoltaic power generation
  - Advanced Ni hydrogen battery
  - Mobile devices

#### Capacitor
- Capacitors based on new concept
  - Drastic performance improvement and cost reduction
  - Hybrid with storage battery

### Supporting and related technologies
- HEMS/BEMS/Local-level EMS

### Introduction/diffusion scenario
- For vehicles
  - Public vehicles, Commuters EV for limited-use
  - General Commuter EV
  - Full-spec EV
  - Plug-in HV vehicle
- For stationary use
  - Load leveling
  - Power quality improvement
  - Load change compensation
  - Stabilization of wind power/photovoltaic power generation
  - Local-level EMS
Network Topic in Cool Earth 50

HEMS/BEMS/Local-Level EMS

- Application of HEMS/BEMS technology
- Organic combined technology with HEMS/BEMS and local heat/electricity supply
- Coordination with autonomous local energy demand and supply system
- Local area EMS
- Block-level EMS
- Cluster type (local/city-level) EMS

HEMS (Home Energy Management System)

- Telecommunication hardware technology
- Middleware technology
- In-house sensor network
- Renewable energy integration
- Energy demand and supply analysis/forecasting technology
- Micro sensing technology
- Energy (electricity/heat) storage system integration
- Energy saving technologies such ad DC power supply
- Energy saving cooperation and control by living activity forecasting technology

BEMS (Building Energy Management System)

- Application of HEMS technology
- High efficiency, power saving BEMS
- Next-generation ultra energy saving BEMS
- Integrated/flexible BEMS

Supporting and related technologies

- Next-generation high-efficiency lighting
- Energy-conserving information devices and systems
- Innovative photovoltaic power generation
- Advanced Li ion battery
- High heat insulation and shielding houses and buildings
- Power electronics

Introduction/diffusion scenario

Individual development of communication hardware, middleware and sensor technology

Diffusion of ESCO projects, Development in energy saving businesses such as EPS, Further efficiency and IT development in commercial and household devices

ESCO: Energy Service Company proposing business for energy conservation
Considerations on storage battery for PV

- **Possible Locations of Energy Storage in Grids with PV Systems (in summary)**
  - **In the case of bulk introduction of PV among national electric grids**
    - Bulk storage with PV Power Plant
  - **In the case of distributed approach of PV aggregation in urban residential communities**
    - Battery Station beside distribution substation, as a social infrastructure (its cost met by the society), not for individual PV homes

  **Preferable Principle:**
  Social Cost Minimum to fulfill the balance of local energy supply and demand with local storage.

  **Battery controller gives an additional value – “Scheduled Orderly Power Flow”**
Proposal of Autonomy Enhanced PV Clusters

The Main Objectives:

- Maximize PV installation into a residential community.
- Allow grid power flow downward and upward equally.
- Stabilize the fluctuation of power flow specified by $|\text{PV} - \text{Load}|$ to raise added value for purchase & sale.
- Minimize storage capacity by community-scale optimization.
- Extend to regional DES management in longer-term view.
Possible Solution: Storage Battery + PE

- Local Battery station for the community can be provide for massive PV clusters in conjunction with voltage distribution compensation by power electronics (PE) to accept 100% reversal power flow.
- This battery station can control power between its community and external utility to keep it in a pre-specified pattern.

Pre-specified Profile
Orderly Flow
Anchored to centre

PE*: power electronic controller
Orderly Strategy for External Utility

- Battery Storage
  Autonomy-Enhanced PV Cluster (AE-PVC)
  Function Following Fast Load Orderly PW Purchase

- Necessary Info
  Next Day Load
  Next day PV Gen
  Battery SOC
  Next Day Shortage
  Power Pool Trends

Orderly Purchase from outside

- P/Q Zero Connection or Isolating
  (Winter Term: PC P Shortage)

Constant Power from outside without Q

Discharge for Load

Charge or HP-hot water

Load Profile

PV Gen

Charge

Discharge

Next Day Load
Next day PV Gen
Battery SOC
Next Day Shortage
Power Pool Trends

Submit Purchase Plan to power pool prior to 24 hours before

Necessary Info

Orderly PW Purchase

Load Profile

Charge

Discharge for Load

PV Gen

Charge or HP-hot water

Load Profile

Discharge

Next Day Load
Next day PV Gen
Battery SOC
Next Day Shortage
Power Pool Trends

Submit Purchase Plan to power pool prior to 24 hours before

Necessary Info
Autonomy-Enhanced, Community-base PV Cluster Concept by employing Active Control

Less Interactive

Inter-Utility Connector (Router)

Community Substation

AC Storage Device

Series Power Device

Series Power Device

Inter-Feeder Router (LPC)

Shunt Power Device

PV

100% PV Clusters

Autonomy Enhanced Community Grids

AE-PVC Concept
Decentralized, Autonomous, Asynchronous Power Router - Basic Concept

Power Router: Asynchronous, i-controlled AC-AC converter

- \( P_{PV} \): Current controlled PV Inv.,
- \( P_A, P_B \): autonomously balanced by \textbf{freq.-droop} for each town.,
- \( Q_A, Q_B \): autonomously balanced by \textbf{voltage-droop} for each town,
- \( P_{AB}, Q_{AB} \): adjusted according to \( \Delta f_A \sim \Delta f_B \) (and \( \cdot V_A \sim \cdot V_B \))

Source: K. Kurokawa: Further considerations on solar PV community concept consisting of massive roof-top PVs and domestic loads, 22nd EU-PVSEC, Milan, 3-7 Sept. 2007, PL2.
Decentralized, Autonomous Power Router
Expected Basic Control Functions

- Router Functions realized by **Asynchronous** Power Conditioners such as BTB, Matrix Converters, etc.
- Current control on individual PVs and droop V/F control on battery station(s).
- Power Flow Control by localized sensing on router terminals, including **zero P/Q** control.
- Local **Voltage** Control.
- Local **Frequency** Control independent from External Grids
- **Local Frequency** adjusted according to supply/demand balance.
- The possibility of Next Generation Power Electronics by **SiC** Technology for reducing size/cost. (BTB, Matrix C.)
60MW PV Plant: Olmedilla (Cuenca)
Presently World Largest PV Plant
Our Future Directions toward 2100

WBGU: German Advisory Council on Global Change

Primary Energy Supply [EJ/Y]

YEAR

2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100

Geothermal
Other REs
Solar heat
Solar electricity
Wind
Biomass adv
Biomass trad
Hydro-PW
Nuclear PW
Gas
Coal
Oil

TOKYO TECH

42 kurochan
Proposed Scenarios toward 2030-2050 & beyond

PV module Technology

1G  2G  3G  Recycle

Developing Region Scenario

1G  2G  3G

Community Scale Grid Scenario (Micro-Grid)

Rooftop PV + Storage

Global Energy Mix

Mini-Grid

VLS-PV to Global-Grid

Large Scale to Very Large Scale PV + Storage

International to Global Grid
Possible MEDITERRANEAN NETWORK TO GLOBAL NETWORK

IEA PVPS Task8
Necessary Steps to Realise the Vision

- Solar (CSP)
- Solar (PV)
- Wind
- Hydro
- Biomass
- Geothermal

HDVC before 2020
HDVC after 2020

Picture source: TREC
**Recommendations**

- Solar PV is not a niche energy source: it is clearly a major contribution for the 21st century energy portfolio.

- Residential PV rooftops are the first option - meaningful for urban communities; they also play a part of the earlier investment in industrial applications for stations.

- Improvements in the distribution grids are required to integrate massive aggregation of residential PV and must be part of urban planning.

- Higher Penetration requires the modification of grid operation for balancing demand/supply and the deregulation of power systems.

- Bulk PV systems will require substantial social support to move forward in the 21st century.

- Power grid modification by the principle of Social Cost Minimum and its cost shared by the whole society with consensus.
The particularity of the power network incorporating with the aggregation of distributed PV systems

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[PV2030]

[Network Concepts and Advanced PCSs for PVs]
(20) K. Kurokawa: Further considerations on solar PV community concept consisting of massive roof-top PVs and domestic loads, 22nd EU-PVSEC, Milan, 3-7 Sept. 2007, PL2.
[Evaluation for NEDO/City of Ota Project]


