Commercializing Technologies in the Eilat Eilot Renewable Energy Project

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Living at the Desert...
Turning disadvantages into advantages on the way to Regional Energy Independence, setting an example and becoming a model for solving the global energy crisis

**Mission**

To develop a vertically integrated renewable energy project in the Eilat Eilot region that will generate sustainable regional development and promote Israel's RE industry

**Vision**

Turning disadvantages into advantages on the way to Regional Energy Independence, setting an example and becoming a model for solving the global energy crisis
The Eilat Eilot Model - A Complete Life Cycle For Developing and Commercializing RE Technologies

- Renewable Energy Administration
- Chairmen: Heads of Municipalities
- RE Manager
- Education
- R&D and Academic Programs
- Timna RE Park
- Municipal Economic Company
- Environmental Unit Eilot Eilot Manager
- RETC Pilot Projects & Validation Center
- RETC Incubating Innovation
- Branding, Regulation, Conferences
- R&D Manager
- Technological Center Manager
Bridging the Valley of Death Between Lab and Bankability
Israel’s Leading RE commercialization Platform

• Finding the best site for a specific pilot project to demonstrate real world applications

• Assisting with land allocation, zoning issues, utilization of all relevant national and regional benefits

• Accelerating fund raising for pilot projects by offering a regional framework that provides confidence for investors

• Offering local EPC and maintenance services

• Providing professional, objective monitoring and validation services

• Integrating with other regional RE activities such as academic research and energy production

• Commercial implementation of the technology in Eilat – Eilot and globally

• Exposing and marketing the technology at the conference and through other channels under the Eilat - Eilot RE brand
Preference of RE Technologies in Eilot-Eilat: Solar at Center of Program, Wind and Biomass as Add-ons

- **Small hydro**: Irrelevant in Israel
- **Geothermal**:
  - Complementary limited solution
  - Inclination to commercial/production activity

- **Biomass**: Complementary limited solution
  - Agricultural
  - Methane emission
  - Algae

- **Wind**: Add-on to the move
- **PV Solar**
- **Thermal solar**:
  - Parabolic trough
  - Solar Tower

**Strategy Anchor**

**Technological Maturity**

**Inclination to commercial/production activity**

**Signs for early development stages**

**Suitability for the Arava**

- No room for uniqueness - Worldwide vast experience in the sector
- Issue of suitability for the Arava (problematic locations)
Solar Tower

Aora-Energy Solar Pilot Plant
The Arava Sustainable Energy Technologies Validation Center

Founded and Operated by

The Eilat Eilot Renewable Energy Initiative and the Arava Institute for Environmental Studies

Commercialization of sustainable energy technologies through: real conditions performance testing, demonstrating and exposing of breakthrough technologies. The center will serve as a vehicle for inserting such technologies into the global market with an emphasis on creating a thriving Israeli industry.

The center is part of the Eilat-Eilot sustainable energy initiative founded in 2006 with the aim of developing the region and turning it into a world leader in the field of sustainable energy.
Validation Center
Center for Renewable Energy
and Energy Conservation
of the Arava Institute
Validation Center
Center for Renewable Energy and Energy Conservation of the Arava Institute
Israeli CPV Innovation
RE Technological Center

Perfect access to Israeli RE innovation

- Incubating Israeli RE technologies startups
- Zone for pilots and testing
- Commercialization of academic research
- Partnership with BGU, a leader in RE
- Tender issued by the government who is going to invest up to 20M$ over 5 years period
Technology Center Partners:

- Entrepreneurs:
  - Eilat-Eilot RE initiative
  - Shibolet Roberts LLP
  - Ben-Gurion University
  - Arava Institute
  - Seasoned Professionals

- Investors
  - Ormat
  - Elbit Systems
  - Rafael Industries
  - ProSeed Venture capital
  - Yashir investment house
  - Consensus Business Group
Eilat - Solar City
Implementing Energy Conservation Technologies

Esco

My Planet

Schools

Hotels
Timna RE Industrial Park

Planning

Land Allocation

Pilots, TC, VC, Insudystry, RE Authourty

RE Power Plants

Timna - RE Industrial Park
6000 Dunams (1500 Acres)
The Timna Solar Energy Initiative
eSolar builds an individual 46 MW power unit on 160 acres (64 hectares).
Solar Thermal and Desalination as a Pilot project for European/North African Solar Energy Plan

Concentrated Solar Thermal Power (CSP):
- Solar heat storage for day/night operation
- Hybrid operation for secured power
- Power & desalination in cogeneration

Sketch of High-Voltage Direct Current (HVDC) grid: Power transmission losses from the Middle East and North Africa (MENA) to Europe less than 15%.

Power generation with CSP and transmission via future EU-MENA grid: 5 - 7 EuroCent/kWh

Various studies and further information at www.TREC-EUMENA.net
2007

The First International Conference on Sustainable Energy as a Catalyst for Regional Development

June 5-7, 2007 | Eilat, Israel
Belongs to Those who prepare for it

Tomorrow

Today

www.eilatenergy.com
Eilat – Eilot Renewable Energy Conference & Exhibition
February 16-18, 2010 • Herods Hotel, Eilat Israel

The Eilat-Eilot Renewable Energy Administration invites you to attend the third renewable energy conference.
Looking forward to seeing you,
The Eilat-Eilot Renewable Energy Administration

The convention and the exhibition are a platform for technological innovation, policies, implementation and business opportunities in the renewable energy field.

For more details, please contact the Eilat-Eilot Administration 08-6371717 www.eilatenergy.org

organizer:

www.eilatenergy.org
Potential for Distributed Photovoltaic Electricity Production in Israel

Ran Vardimon
Weizmann Institute of Science
Acknowledgements

Prof. David Cahen and Prof. Igor Lubomirsky
Weizmann Institute of Science

Efrat Avraham and Eyal Meharian
Israel Central Bureau of Statistics

Yoav Sagi and Guy Nizri
The Open Landscape Institute ("מכון דשא")
Advantages of PV Systems on Rooftops

• Eliminate the need for vast tracts of land
• Reduce transmission costs
• Reduce solar heating

However, is there enough rooftop area?
(to produce a significant portion of Israel’s electricity demand)
Yearly Insolation vs. DC Panel Output

$kWh \ m^{-2} \ yr^{-1}$

- **Jerusalem**: 1991 kWh m$^{-2}$ yr$^{-1}$ (1458 kWh m$^{-2}$ yr$^{-1}$ for DC panel output)
- **Tel Aviv**: 1883 kWh m$^{-2}$ yr$^{-1}$ (1381 kWh m$^{-2}$ yr$^{-1}$ for DC panel output)
- **Haifa**: 2043 kWh m$^{-2}$ yr$^{-1}$ (1497 kWh m$^{-2}$ yr$^{-1}$ for DC panel output)
- **Beersheba**: 2122 kWh m$^{-2}$ yr$^{-1}$ (1550 kWh m$^{-2}$ yr$^{-1}$ for DC panel output)
- **Eilat**: 1422 kWh m$^{-2}$ yr$^{-1}$ (1197 kWh m$^{-2}$ yr$^{-1}$ for DC panel output)

Legend:
- Blue: Global insolation
- Red: DC panel output (per kWp)
Average Yearly Output
Output varies slightly between locations in Israel (-/+ 8%)

Average Yearly DC output for a 1kWp system
1460 kWh m\(^{-2}\)

Panel Efficiency - 16%
relatively high-efficiency commercially available panel.

DC output per m\(^2\)
1460 * 0.16 = 233 kWh/m\(^2\)
PV Output in Israel

DC – AC Conversion Efficiency - 90% mean inverter and wiring losses.

Average Yearly AC panel Output
233 kWh/m² * 0.9 = 210 kWh/m²
Geographic Information System (GIS) Calculations were performed

1) Bound all buildings by polygons

2) Sum polygon areas

**Total Rooftop Area in Israel:** 251 km²
# Rooftop Area

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Total Area [km²]</th>
<th>Avg. Area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>188.7</td>
<td>195</td>
</tr>
<tr>
<td>Industrial</td>
<td>24.0</td>
<td>954</td>
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<tr>
<td>Agricultural</td>
<td>23.8</td>
<td>393</td>
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<tr>
<td>Warehouse</td>
<td>6.5</td>
<td>35</td>
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<tr>
<td>Public</td>
<td>4.1</td>
<td>870</td>
</tr>
<tr>
<td>Educational</td>
<td>2.6</td>
<td>495</td>
</tr>
<tr>
<td>Mall</td>
<td>1.7</td>
<td>1064</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>251.5</strong></td>
<td><strong>201</strong></td>
</tr>
</tbody>
</table>
Available Rooftop Area

Most of the rooftop area can’t be used

• Structures
• HVAC (Heating, Ventilation, AC)
• Shading
• Pitched roofs
• Solar water-heaters (especially in Israel)

Picture from http://gis.cityofboston.gov/solarboston/
Available Rooftop Area

% = (Usable Area) / (Total Rooftop Area)

<table>
<thead>
<tr>
<th>Roof Type</th>
<th>U.S.</th>
<th>Israel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitched Roof</td>
<td>18%</td>
<td>20%</td>
</tr>
<tr>
<td>Flat Roof</td>
<td>65%</td>
<td>Residential - 50-70% Commercial/Industrial - up to 90%</td>
</tr>
<tr>
<td>Mean</td>
<td>32%</td>
<td>30%</td>
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</table>

U.S. Mean Availability - calculated knowing the pitched/flat roof ratio.
Israel Mean Availability - a conservative estimate.
20% of rooftops are > 800m² (50.1 km² total)
800m² rooftop = 64kWp system (with 50% area availability)
Rooftop area can be used efficiently...

Googleplex in California
1.2 Installed MW
### Total PV Potential

#### Total Potential Scenario
- 16% panels
- all rooftops (30% availability)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Rooftop Area</td>
<td>252 km²</td>
</tr>
<tr>
<td>Available Area</td>
<td>76 km²</td>
</tr>
<tr>
<td>Capacity</td>
<td>12,000 MW_p</td>
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<tr>
<td>Output</td>
<td>16 TWh yr⁻¹</td>
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</tbody>
</table>

#### Cautious Scenario
- 10% panels
- rooftops > 800m² (50% availability)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Rooftop Area</td>
<td>50 km²</td>
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<tr>
<td>Available Area</td>
<td>25 km²</td>
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<tr>
<td>Capacity</td>
<td>2,500 MW_p</td>
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<tr>
<td>Output</td>
<td>3.3 TWh yr⁻¹</td>
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</table>

**National Electricity Demand:** 50 TWh yr⁻¹

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Output / National Demand</td>
<td>32%</td>
</tr>
<tr>
<td>Output / National Demand</td>
<td>7%</td>
</tr>
</tbody>
</table>
Conclusions

32% of Israel’s electricity demand can be met using rooftops.

10-15% - economic bound for solar electricity with no energy storage.

Hence, available rooftop area is sufficient for producing all feasible solar electricity.

There is no shortage of rooftop area
**Where to start?**

Where it makes most economical sense.

**Eilat** has:

- highest insolation values
- highest rooftop area per capita
- no nearby power plant

**Eilat** seems as an obvious place to begin a city-wide rooftop PV program.
WHEN THE WORLD RUNS OUT OF OIL
A RIGOROUS WAY TO CONSIDER ALTERNATIVES

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WHEN WILL THE SHORTAGE BE FELT?

- There is no doubt that the amount of oil is finite
- The shortage will be felt when need exceeds production (not when all the wells dry out)
- Past experience: production peak is reached when half the known reserve has been used
- Early estimates pointed at 2005 (leading to record high prices of $150/B)
EARLY ESTIMATES WHERE OBVIOUSLY WRONG

- Present high fluctuations in price indicate that we are close to the turning point (when consumption exceeds production).
- All experts agree that the crisis will come before 2050
- By the beginning of the 22nd century, the economic patterns will change
- Oil will still be available, but only for special uses
THE IMMENSITY OF THE PROBLEM

- World consumption is about 80 M barrels/day (about 11 M ton/day)
- 7 barrels. ≈ 1 Ton
- Amount of CO$_2$ produced ≈ 35 M ton/day
- Amount of H$_2$O produced ≈ 14 M ton/day
- A curiosity: (CO$_2$/CH$_2$) = 44/14 = 22/7 = 3.14286. This happens to be the value used by the ancient Egyptians for π = 3.14159. (3.14286/ 3.14159) = 1.00040
ALTERNATIVE SOURCES OF ENERGY

- **COAL:**
  - Reserves expected to last for 300 years. **BUT:**
  - Highly polluting
  - Open-pit mining is opposed by environmentalists
  - Will have to be converted to liquid
  - Technology for coal liquefaction exists
  - Coal will also run out eventually
NUCLEAR

- Technology is well established
- Sufficient reserves of Uranium
- Waste disposal is problematic
- Strong public opposition in some countries
- Opposition may wane if shortage in energy becomes critical
- Danger of nuclear proliferation increases
Controlled nuclear fusion

A major breakthrough in technology is needed

If successful, it will solve the energy problem “forever” (i.e. many thousands of years)

But even if successful, will it ever be safe?

Will there be nuclear waste created?

Will it lead to proliferation of hydrogen bombs?
SAVING ENERGY

- Saving energy is important, but it will not solve the problem
- Using waste is important, but limited in scope
- Example
  - Using waste oil in the kitchen to make diesel fuel
  - Making diesel fuel from waste during oil change in the car
  - Compare the quantities
    - 1. Driving to work one day 3 L consumed
    - 2. Driving a car between oil changes about 1,000 L
RENEWABLE ENERGY

- **Wind**: useful but limited to certain places,
- **Wave**: and tidal energy. No technology available
- **Solar**: The ultimate renewable energy

- All above have variable energy output and very large-scale energy storage is needed
HOW TO JUDGE A NEW TECHNOLOGY

- **Determine energy balance.**
- **Example:**
  - **Growing corn to make alcohol as fuel**
    - The energy consumed includes:
      - 1. Ploughing, fertilizing
      - 2. Manufacture fertilizers
      - 3. Pump water for irrigation
      - 4. Harvest (fuel for machinery)
      - 5. Shipp the product to the factory
      - 6. Fermentation of the product to make alcohol
      - 7. Waste disposal of fermentation
THE END OF CORN-FOR-FUEL PROJECT

- It is technologically possible
- It was subsidized by government
- It created a shortage of corn for food
- Price for corn and corn-products increased

The (subsidized) cost may make it profitable, but

THE ENERGY BALANCE IS NEGATIVE!!!
STATEMENT OF THE PROBLEM

- The need for energy is of two types:
  - **Stationary**
    - Factories, homes offices etc
  - **Mobile**
    - Transportation (air, surface sea)
- **Technology needed to convert stationary to mobile applications**
STATIONARY ENERGY

- All the need can be provided by photovoltaic energy

<table>
<thead>
<tr>
<th>Area</th>
<th>Total radiation</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m²</td>
<td>1 kW</td>
<td>0.1 kW</td>
</tr>
<tr>
<td>1 km²</td>
<td>10⁶ kW</td>
<td>100 MW</td>
</tr>
<tr>
<td>10 km²</td>
<td>10⁷ kW</td>
<td>1 GW (one power station)</td>
</tr>
<tr>
<td>100 km²</td>
<td>10⁸ kW</td>
<td>10 GW (peak conventional power production in Israel)</td>
</tr>
</tbody>
</table>
PHOTOVOLTAIC PRODUCTION

◆ ADVANTAGES
  - Peak power when most needed
  - Area needed is moderate: 10x10 km for peak, 20x20 km for average rate
  - Small scale “solar farming” in arid desert areas

◆ DISADVANTAGES
  - High cost of solar cells
  - Energy consumed in production of cells
  - Performance depends on weather
  - Energy storage is required
THE HYDROGEN ECONOMY

- Hydrogen is often said to be the best fuel
- Why is hydrogen the best fuel?
WHY IS HYDROGEN THE BEST FUEL?

- It has the highest energy density
  - $\text{H}_2$ \[142 \text{ MJ/kg} = 39.4 \text{ kWh/kg}\]
  - Gasoline \[47 \ 	ext{“} = 13.0 \ 	ext{“}\]
  - Li-Ion battery \[1 \ 	ext{“} = 0.28 \ 	ext{“}\]

- The only product is water

(1 kWh = 3.6 MJ)
WHY IS HYDROGEN NOT THE BEST FUEL?

- Hydrogen is not a source of energy – it must be manufactured!
- It is very difficult to store and transport
- Long-term storage for mobile applications is essentially impossible
- Storage increases the weight dramatically
- The energy density by volume is very low
- H₂ is highly explosive
WHY IS HYDROGEN \textbf{NOT} THE BEST FUEL?

- **Volume energy density, compared to gasoline**

  - **DENSITY, }\rho\{:** \((0.8/\rho)(1/3)\)

    - 350 Atm – 0.024 gm/cm\(^3\) \quad 11
    - 700 Atm – 0.040 \quad 6.7
    - Liquid - 0.070 \quad 3.8
    - LaNi\(_5\)H\(_{6.7}\) - 0.020 \quad 13.3
    - Gasoline - 0.8 \quad 1.00

  - \((0.8/\rho)\) is the ratio of densities
  - \((1/3)\) is the ratio of energy/kg
INHERENT PROBLEMS WITH H₂ AS A FUEL

- **Storage** and **transportation** are problematic since:
  - energy is lost in compression (25%)
  - energy is lost in liquification (35%)
  - Containers are heavy and voluminous.
  - Highly explosive – leakage could cause major urban disaster
THE ULTIMATE ELECTRIC VEHICLES

- Electric trains
- Subways
- Street cars
- Elevated light trains in cities
- Elevated roads for electric bicycles
THE ULTIMATE ELECTRIC PASSENGER CAR

- A hybrid between a car and a tram.
  - Running on overhead electricity on the highway
  - Running on battery in the city

- Particularly suitable for toll highways: speed and distance between cars can be controlled

- Energy used can be monitored
CONCLUSIONS 1

- The human race can survive without fossil fuel, but our way of life will change.
- The main source of energy will be photovoltaic.
- There is a dire need for research in this area.
- Present drive to generate electricity by photovoltaic cell uses existing technology. It is only useful for public relations.

- Storage is a crucial issue for renewable energy.
The electric train is the most efficient electric vehicle

Fast trains should replace air transportation

Vehicles on fixed routes (intercity buses, heavy truck) should run on overhead electric supply, with enough batteries for short-range deviations

Automated passenger cars with overhead electric supply is plausible

Fossil fuel will probably be available in small quantities (compared to preset consumption) for special purposes
OPTIMIST AND PESSIMIST

- An optimist views any problem as an opportunity.

- The pessimist views any opportunity as a problem.
ASSUME A RATIONAL WORLD

- **Stationary energy – available for very long time:**
  - Solar
  - Nuclear, fission ($U^{235}$)
  - Nuclear breeder reactors ($U^{238}$); ($Th^{232}$)
  - Fusion technology: not yet available

- **The challenge**
  - Energy for transportation
  - Should be without fossil fuel and without energy generated from fossil fuel
ELECTRIC CARS POWERED BY SOLAR CELLS

- Assume solar panel of 1m\(^2\) and 20% efficiency
- \(1 \text{kW/m}^2 \times 0.2 = 0.2 \text{ kWh/h}\)
- Average energy collected over 8 hours (50% of peak) \(0.2 \times 8 \times 0.5 = 0.8 \text{kWh/day}\)

- Power for average passenger car
- \(30 \text{ kW} = \text{kWh/h} = 0.5 \text{kWh/min}\)
- \(0.8/0.5 = 1.6 \text{ min}\)
- FULL DAY CHARGING YIELDS ENERGY FOR 1.6 MIN
ELECTRIC CARS

- The electric car is not a solution, as long as electricity is produced from fossil fuel
- Some saving in energy may result, but not much.
- Fossil fuel $\rightarrow$ Electricity at home $40\%$ efficiency
- Fast charge and discharge $70 - 80\%$
- Total efficiency $28 - 32\%$

- Higher efficiency can be achieved by:
  - Reducing weight (composite materials)
  - Diesel Engines
FAST TRAINS TO REPLACE AIRPLANES

- The technology for fast electric trains (350km/h).
- Electric trains use stationary power
- This could replace air transportation for distances up to 1,200 km
  - Washington – Boston
  - Chicago – Cleveland
  - San Francisco – Seattle
  - Toronto – Ottawa - Montreal

Helena Faitelson

Prof. Mordechai Shechter

Dr. Ruslana Rachel Palatnik
Outline

- Motivation
- Aims of study
- General Equilibrium Model overview.
- Model implementation in the research.
Motivation
Global Warming Process

• A worldwide issue of concern
• Globally coordinated action
• The Kyoto protocol (1997)
• Post Kyoto agreement: Bali (2007), Copenhagen (2009)

CO₂, CH₄, N₂O, CFCs...
What is the economist’s bottom line here?

- Fossil fuel use generates CO$_2$ emissions
- Carbon cycle: redistributes around atmosphere, oceans, etc.
- The emissions-climate-impacts-policy nexus
- Measures to control emissions (limits, taxes, subsidies, …)
- Climate system: change in radiative warming, precipitation, ocean currents, sea level rise, …
- Impacts on ecosystems, agriculture, diseases, …
The aims of the study:

- Performing policies analysis using static CGE model for the Israeli economy:
  - Build the most updated database for model benchmarking.
  - Estimate elasticity of substitution in production function of Israeli market given econometric data.
  - Calculate impact of Greenhouse Gases (GHG) abating policies.
  - Perform evaluation of tax alternatives and analyze their impact on welfare and unemployment.
  - Compare alternatives in perspective of tax revenue recycling and propose the optimal one.
The Dynamics Of CGE

Consumers (Households, Government)

Maximise Welfare From Consumption

Minimise Cost Of Production

Output Markets Goods And Services

Demand And Supply Functions “Mimic” Observed Economic Systems: Parameters Are Calibrated On “Real” Data

Input Markets Capital, Labour, Land, Natural Resources

Demand Constrained By Income

Constrained By Technology

Supply

Demand

Income

Demand

Supply

Income

Producers (Firms, Government)

Constrained

Minimise Cost Of Production
The Model: General Features

• Market clearing in:
  - All markets
  - Goods and services
  - Production factors

• Zero excess profits
  - Total revenue equals to total cost

• Balanced budget for each agent
  - Expenditure equals to income
1. Indirect taxes less subsidies on products;
2. Taxes less subsidies on production;
3. Labor taxes;
4. Capital taxes;
5. Taxes on households;
6. Taxes on imports;
Sectoral mapping

1. AFF  Agriculture
2. ROIL  Refined petroleum
3. COIL  Extraction of crude petroleum and natural gas
4. COAL  Mining and agglomeration of hard coal
5. MNF  Manufacturing
6. ELE  Electricity
7. WAT  Water
8. CON  Construction
9. TRD  Wholesale and retail trade repairs of vehicles
10. ASR  Accommodation services and restaurants
11. TRC  Transport storage and communications
12. BIF  Banking insurance and other financial institutions
13. BAC  Real estate renting and business activities
14. PAD  Public administration
15. EDU  Education
16. HWS  Health services and welfare and social work
17. CSS  Community social personal and other services
18. IBS  Imputed bank services and general expenses

From 162-industry aggregation tables
## Data: Macro Social Accounting Matrix (2004 in Million NIS)

<table>
<thead>
<tr>
<th></th>
<th>Activities</th>
<th>Commodities</th>
<th>Factors</th>
<th>Households</th>
<th>Government</th>
<th>Savings</th>
<th>Rest of World</th>
<th>Total</th>
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<tbody>
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<td>1,020,736</td>
<td></td>
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<td>Households</td>
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<td>35,523</td>
<td>-26,383</td>
<td>91,770</td>
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<td>Rest of World</td>
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<td>96,445</td>
<td>19,987</td>
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<td>1,313,574</td>
<td>499,683</td>
<td>369,326</td>
<td>214,576</td>
<td>100,910</td>
<td>376,686</td>
<td></td>
</tr>
</tbody>
</table>
The Model: Nesting Structure of the Production Function

Production:
Nested production structure using CES family of functions.
Elasticity of substitution between Capital(K) and Labor(L) is estimated from Israeli econometric data.
Econometric data was available only for sectors, presented in the table.

Same estimated value is used for each sub-sector:
- Elasticity of substitution in Electricity and Water separate sectors will be 0.55

P-value represent statistical test where null hypothesis is zero elasticity of substitution.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Elasticity of substitution</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>0.85</td>
<td>2.54E-27</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>0.65</td>
<td>1.58E-38</td>
</tr>
<tr>
<td>Water &amp; Electricity</td>
<td>0.55</td>
<td>4.03E-30</td>
</tr>
<tr>
<td>Trade &amp; Services</td>
<td>0.39</td>
<td>3.81E-34</td>
</tr>
</tbody>
</table>
Model simulation results

● Assumed:
  - Carbon tax of 50, 100, 150, and 200 NIS per ton of emitted gas.

● Calculated:
  - Emission vs. carbon tax per sector.
  - Abatement vs. carbon tax per sector.
  - Gross Domestic Product (GDP) and welfare vs. carbon tax.
Emission (ktons) vs. tax per sector

Impact of Carbon tax on Carbon Emission

Electricity sector is the mostly emitted.
Emission (ktons) abatement vs. carbon tax per sector

Sectoral abatement curves

Carbon price

Emission reduced

- hhold
- Agric
- Electricity
- Refined oil
- Manufactr
- Transport
GDP and welfare vs. Carbon tax

welfare and GDP change due to carbon tax

<table>
<thead>
<tr>
<th>carbon price</th>
<th>%welfare</th>
<th>%gdp</th>
</tr>
</thead>
<tbody>
<tr>
<td>199.99</td>
<td>-0.2</td>
<td>-0.6</td>
</tr>
<tr>
<td>149.99</td>
<td>-0.4</td>
<td>-0.8</td>
</tr>
<tr>
<td>100.00</td>
<td>-0.6</td>
<td>-1.0</td>
</tr>
<tr>
<td>50.00</td>
<td>-0.8</td>
<td>-1.2</td>
</tr>
<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Conclusions and Next steps

**Conclusions:**
- Carbon taxes cause to CO2 emission reduction in whole economy.
- Impact of Carbon taxes on GDP and welfare is small.

**Next steps:**
- Complete simulation with SAM matrix for 2004 and estimated elasticity of substitution.
- Analyze other policies.
References

Grid Requirements for incorporating electricity generated by large Photovoltaic system: The case of the Israeli grid

A. A. Solomon*, G. Meron**, D. Faiman*

*Department of solar energy and Environmental Physics, Ben-Gurion University the Negev
** Israel Electric Corporation.
Introduction

- Grid operation
- Challenges of adding large PV systems to grid
- Grid matching algorithm
- Results
Typical Diurnal demand profile
Grid Operation

Typical weekly IEC load profiles for each season of the week
Challenges of adding large PV energy into grid

Hourly generation [MW]

Time [hr]

Static mode  1-axis mode  2-axis mode  1X CPV

a) Jan. 2 - 6, 2006

b) Jul. 3 - 7, 2006
PV-Grid Matching Algorithm

Ideal case

an hour - by - hour Ratio = \( \frac{P_{PV}}{P_{grid}} \)

No dump system size is:

\( ND = \frac{1}{\max(R)} \)

\( \max(R) \) - the maximum hourly value of observed ratio for the entire year of data.

Hourly power output of the ND system is:

\( P_{ND} = ND \cdot p \)

\( p \) – hourly output of 1 MWp PV system

Say \( Q \) and \( P1 \) Matrices of the equal size. \( Q \) being a size matrix, while \( P1 \) is a matrix containing hourly output of 1 MWp PV system repeated in its columns.

\[
Q = ND^* \begin{bmatrix} 1 & 1 + m & 1 + 2m & \cdots & 1 + km \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 + m & \cdots & \cdots & 1 + km \end{bmatrix}
\]

\[
P1 = \begin{bmatrix} p_1 & p_1 & p_1 & \cdots & p_1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{8760} & p_{8760} & \cdots & \cdots & p_{8760} \end{bmatrix}
\]
PV-grid Matching algorithm

Hourly output of arbitrarily large PV system is given by taking Hadamard product of $Q$ and $P_1$.

$$ P = Q \cdot P_1 $$

If matrix $T$ is created in similar way to $P_1$

$$ T = \begin{bmatrix} t_1 & t_1 & t_1 & \ldots & t_1 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ t_{8760} & t_{8760} & \cdot & \cdot & t_{8760} \end{bmatrix} $$

An attempted PV input is approximated as:

$$ A = P - T $$

Take logical matrix $H$ in which

$$ H_{i,j} = \begin{cases} 1, & \text{if } (A_{i,j} > 0) \\ 0, & \text{if } (A_{i,j} \leq 0) \end{cases} $$

The dumped energy ‘$D$’ and the useful energy ‘$U$’ matrix are obtained as:

$$ D = A \cdot H \quad U = P - D $$
PV-grid Matching algorithm

**A more realistic case**

Grid flexibility

$$ff = \frac{t_{\text{max}} - t_{\text{min}}}{t_{\text{max}}}$$

The base load part of the hourly load:

$$[1 - ff] \cdot t_{\text{max}}$$

Hourly solarizable load:

$$l_{Si} = t_i - [1 - ff] \cdot t_{\text{max}}$$

Solarizable load matrix is:

$$Y = \begin{bmatrix} l_{S1,1} & l_{S1,j} & \cdots & l_{S1,k+1} \\ \vdots & \vdots & \ddots & \vdots \\ l_{S8760,1} & l_{S8760,j} & \cdots & l_{S8760,k+1} \end{bmatrix}$$

Define logical matrices $J$ and $K$ as follows:

$$J_{i,j} = \begin{cases} 1, & \text{if } (Y_{i,j} > 0) \\ 0, & \text{if } (Y_{i,j} \leq 0) \end{cases}$$

$$K_{i,j} = \begin{cases} 1, & \text{if } (Y_{i,j} \leq 0) \\ 0, & \text{if } (Y_{i,j} > 0) \end{cases}$$
PV grid Matching algorithm

Hourly solarizable load matrix:

\[ B = Y \otimes J \]

Matrix of Grid surplus energy

\[ C = Y \otimes K \]

The PV ND size at a given flexibility is:

\[ \text{ND}_{ff} = \frac{1}{\max(V_j)} \]

where

\[ V = \frac{P1}{B} \]

Storage system calculations:

\[
Q1 = ND_{ff} \times \begin{bmatrix}
1 & 1+m & 1+2m & \ldots & 1+km \\
& & & & \\
& & & & \\
1 & 1+m & \ldots & \ldots & 1+km \\
\end{bmatrix}
\]

\[
T1 = \begin{bmatrix}
l_{s1} & l_{s1} & l_{s1} & \ldots & l_{s1} \\
& & & & \\
& & & & \\
l_{s8760} & l_{s8760} & \ldots & \ldots & l_{s8760} \\
\end{bmatrix}
\]

Hourly output of arbitrary large PV system:

\[ P2 = Q1 \otimes P1 \]
Attempted direct PV injection:

\[ A1 = P2 - T1 \]

\[ H1_{i,j} = \begin{cases} 
1, & \text{if } (A1_{i,j} \geq 0) \\
0, & \text{if } (A1_{i,j} < 0) 
\end{cases} \]

\[ W_{i,j} = \begin{cases} 
1, & \text{if } (A1_{i,j} < 0) \\
0, & \text{if } (A1_{i,j} \leq 0) 
\end{cases} \]

A matrix \( S \) can be defined as follow:

\[ S_i = a_{i-1} \bullet S_{i-1} \bullet H1_i + \eta_c (A1_i \bullet H1_i) + \frac{A1_i \bullet W_i \bullet d_i}{\eta_d} + a_{i-1} \bullet S_{i-1} \bullet d_i \bullet W_i + \eta_d (a_{i-1} \bullet S_{i-1} \bullet z_i \bullet W_i) + A1_i \bullet W_i \bullet z_i \]

Where the vectors:

\[ a_{i-1} = (S_{i-1}, \geq 0) \]

\[ d_i = (a_{i-1} \bullet W_i \bullet S_{i-1}, \geq -\frac{A1_i \bullet W_i}{\eta_d}) \]

\[ z_i = (\frac{a_{i-1} \bullet S_{i-1,j} \bullet W_i}{\eta_d} < -W_i \bullet A1_i) \]
References:


• Solomon, A.A., D. Faiman and G. Meron. Properties and uses of storage for enhancing the grid penetration of very large scale photovoltaic systems. - *Energy Policy* (2010), Accepted
Results: Grid matching

Interaction of ND-size PV system and IEC grid ($ff = 1$) based on data for (a) January 1-7, (b) March 19-25 and (c) July 2-8, 2006
Grid matching,

ND size at different flexibility, March 19-25, 2006 for all the three cases


**Base load**

**Potential solarizable load**

**Solarized part of the load**
Change in ND size PV penetration with Flexibility factor
Effect of exceeding ND size on the matching of the load requirement.
Possible optimal flexibility and penetration

Res. Cont.

Weekly solar match at the potential annual ramping range, 5% energy dumping
Energy storage use, Cont.....

![Graph showing daily surplus PV energy as a percentage of maximum daily demand over 365 days. The graph compares three PV sizes: 7ND, 5ND, and 3ND. The x-axis represents day number (1 = Jan. 1, 2006), and the y-axis represents daily surplus PV energy as a percentage of the maximum daily demand. The graph indicates fluctuations in energy surplus throughout the year with different patterns for each PV size.]
Energy storage use,

Daily energy capacity, $ff = 0.7$

- PV size = 3ND
- PV size = 5 ND
- PV size = 7 ND
Energy storage use,

Daily surplus PV energy as a fraction of daily solarizable load, $ff = 0.7$

Daily surplus PV energy/daily solarizable load

Day number (1 = Jan. 1, 2006)

PV size = 7ND
PV size = 5ND
PV size = 3ND

PV size = 7ND
PV size = 5ND
PV size = 3ND
Energy storage use,

Annual required energy capacity vs PV system size

- $ff = 0.65$
- $ff = 0.7$
- $ff = 0.8$
- $ff = 1$

Energy capacity [GWh]

PV system size [multiples of ND]

Annual required energy capacity vs PV system size
Energy storage use, Cont.....

Daily power capacity, $ff = 0.7$

- PV size = 3 ND
- PV size = 5 ND
- PV size = 7 ND
Energy storage use,

Annual required power capacity vs PV system size

- $ff = 0.65$
- $ff = 0.7$
- $ff = 0.8$
- $ff = 1$

**Annual required power capacity vs PV system size**
Energy storage use, Cont.....
Energy storage use,

Penetration vs Capacity ratio

- ff = 0.65
- ff = 0.7
- ff = 0.8
- ff = 1

Penetration [% annual demand]

Penetration vs Capacity ratio [h]
### Summary of typical data for storage with approximately 100 GWh energy capacity

<table>
<thead>
<tr>
<th>ff</th>
<th>Power capacity [GW]</th>
<th>Capacity ratio [hr]</th>
<th>Penetration [% annual demand]</th>
<th>Energy loss [% PV generation]*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65</td>
<td>5.4</td>
<td>15.4</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>0.7</td>
<td>7.3</td>
<td>13.0</td>
<td>32.6</td>
<td>10.4</td>
</tr>
<tr>
<td>0.8</td>
<td>10.7</td>
<td>8.6</td>
<td>46.0</td>
<td>11.5</td>
</tr>
<tr>
<td>0.9</td>
<td>14.4</td>
<td>7.2</td>
<td>58.9</td>
<td>12.1</td>
</tr>
<tr>
<td>1</td>
<td>17.7</td>
<td>5.2</td>
<td>70.2</td>
<td>12.2</td>
</tr>
</tbody>
</table>

*Due to storage inefficiency only

### Summarizing impact of PV energy dumping from a system with 100 GWh of storage energy capacity

<table>
<thead>
<tr>
<th>ff</th>
<th>Power capacity [GW]</th>
<th>Penetration [% annual demand]</th>
<th>Loss limited to storage inefficiency alone</th>
<th>Total loss increased to 20 % of PV generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>7.3</td>
<td>32.6 (10.4 %*)</td>
<td>42.2</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>10.7</td>
<td>46.0 (11.5%*)</td>
<td>58.6</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>17.7</td>
<td>70.2 (12.2%*)</td>
<td>88.5</td>
<td></td>
</tr>
</tbody>
</table>

* Percentage of PV generation lost by storage inefficiency
Energy storage use,

Weekly contribution of the IEC daily demand from PV, storage, fossil fuel fired plants.
General Conclusion

- Grid matching of Large PV systems depends on the seasonal and diurnal output profiles of the system and the corresponding load profile, the capability of the power system to increase their compatibility.
- Properly designed storage and accurate forecasting technologies, significantly increase their grid compatibility. Specific combinations have shown approximately 90% potential grid penetration of PV energy.
- Based on adequate knowledge of the seasonal and diurnal variation of intermittent energy resources and demand profile, it is possible to design a new type of grid that can absorb substantial amount of intermittent energy if proper storage technologies are available.
- In case of such grid restructuring, our mathematical formulism is hoped to be a useful tool for grid scheduling. It is also a useful tool for investigating the generality of many of the IEC results for other grids.
Acknowledgments

✔ Israel Ministry for National Infrastructures
✔ Tom Hansen, TEP, Tukson, Arizona
✔ The Bona Terra Foundation and Albert Katz Graduate School of Desert Studies
✔ Staffs and students at Ben-Gurion solar center
✔ Kreitmann School of Advanced Studies
Full landscape of aplanatic optics for solar concentration near the thermodynamic limit

Natalia Ostroumov, Jeffrey M. Gordon and Daniel Feuermann


Department of Solar Energy and Environmental Physics, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus 84990, Israel
Historical notes

- 1905, K. Schwarzschild: The notion of aplanatism was proposed
- 1957, A.K. Head: Analytic solution for near-field dual-mirror aplanat
- 2002, R.V. Willstrop & D. Lynden-Bell: Analytic solution for far-field dual-mirror aplanat
- 2005, Gordon et al: Aplanats as superior concentrators
- Today: Full panorama of solutions viable for concentration
Relevance for industrial applications

- CPV with passive cooling
- CPV with active cooling
- Solar thermal concentration
- Infrared concentration
- Collimating light – (concentration “in reverse”)

Advantages of dual mirror aplanats

- One-optic-one-cell
- Analytical formulation
- Avoiding chromatic aberrations
- Reasonable aspect ratio (AR)
- No optical bonds to the cell (at no loss in efficiency or concentration)

Approaching the thermodynamic limit to flux concentration
A perfect concentrator...

- Fundamental limit to solar concentration

\[ C_{Max,3D} = \left( \frac{\sin \theta_{out}}{\sin \theta_{in}} \right)^2 = \frac{NA_{out}^2}{(\sin \theta_{in})^2} \]

<table>
<thead>
<tr>
<th>NAout</th>
<th>θin (mrad)</th>
<th>Cmax(3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>5</td>
<td>32,400</td>
</tr>
<tr>
<td>1.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>20</td>
<td>2,025</td>
</tr>
</tbody>
</table>
• Image fidelity is determined by the aberrations of the system.
• There is an infinite number of distinctive aberrations.
• We can get closer to the thermodynamic limit by eliminating aberrations.
• The number of aberrations that can be eliminated in an optical system is equal to the number of the contours in the system.
Aplanats

- Aplanats are imaging systems, made of two contours, which eliminate completely spherical aberration and coma.
- For up to 20 mrad field angle, the dominant aberrations are spherical aberration and coma.

Spherical (zeroth-order) aberration

Positive transverse coma

Focal plane
Aplanat design principles

• Fermat’s principle
L₀ + L₁ + L₂ = Const

• Abbe sine condition
r = f * sin (ϕ)
Aplanat design principles

Parameters of the system: $f$, $K$, $S$
Aplanat classification

(1) S and K signs

(2) Absorber orientation: Up/Down
Results

1. \( S > 0 \) \( K > 0 \) up-facing

2. \( S > 0 \) \( K > 0 \) down-facing

3a. \( S < 0 \) \( K < 0 \) up-facing

3b. \( S < 0 \) \( K < 0 \) up-facing
Results

4a. $S<0 \ K<0$ down-facing

5. $S>0 \ K<0$ up-facing

These classes are unphysical (total blocking).

4b. $S<0 \ K<0$ down-facing

6. $S>0 \ K<0$ down-facing

7. $S<0 \ K>0$ up-facing

8. $S<0 \ K>0$ down-facing
Summary

• Basic classification scheme that allows the identification of a variety of distinct optical systems with distinct properties was suggested:
  – Applied on dual mirror aplanatas to reveal those feasible for sun concentration.
  – Can be applied to reveal feasible optics for other applications as well

• Identification of several previously unrecognized classes of concentrators.

• Same classification can apply for:
  – Near-field aplanats
  – Simultaneous method of surfaces (SMS)
Thanks:

- Prof’ Jeffrey M. Gordon, Prof’ Daniel Feuermann, Alex Goldstein

- Our research group:
  - Baruch Hirsch, Avi Braun, Efrat Greenwald, Dotan Babai and Dr. Alexis Vossier.

THANK YOU!
Results

1. S>0 K>0 up-facing

- **S = 0.43, K = 0.0385, N_A_{out} = 0.9**
- This particular configuration achieves the compactness limit of an aspect ratio of 0.25

<table>
<thead>
<tr>
<th>$\theta_{in}$ (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>$C/C_{max}$ (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.03</td>
<td>0.93</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.81</td>
</tr>
</tbody>
</table>
2. $S>0 \ K>0$ down-facing

- $s = 5.0$, $K = 0.00477$, $NA = 0.9$
- $\pi - \text{ArcSin}(NA) \leq \phi \leq 2.93$.
- (a) Full view. (b) Magnified view near the focal plane.

### Results

<table>
<thead>
<tr>
<th>Concentrator</th>
<th>$\theta_s$ (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>Losses for an extended source (equal-étendue designs)</th>
<th>$C/C_{\text{max}}$ (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s = 5.0$ \ K = 0.00477</td>
<td>5</td>
<td>0.0545</td>
<td>0.32</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>0.40</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>0.41</td>
<td>0.535</td>
</tr>
</tbody>
</table>
Results

3a. S<0 K<0 up-facing

- $s = -0.61$, $K = -0.23$, $NA_{out} = 0.9$,
- 3.5% intrinsic loss

<table>
<thead>
<tr>
<th>Concentrator</th>
<th>$\theta_s$ (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>Losses for an extended source (equal-étendue designs)</th>
<th>$C/C_{max}$ (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s = -0.61$, $K = -0.23$</td>
<td>5</td>
<td>0.035</td>
<td>0.01</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>0.02</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>0.055</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Results

3b. $S < 0 \ K < 0$ up-facing

- $S = -0.162, \ K = -1.072, \ NA_{out} = 0.9$

<table>
<thead>
<tr>
<th>$\theta_{in}$ (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>$C/C_{max}$ (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.03</td>
<td>0.93</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.825</td>
</tr>
</tbody>
</table>
Results

4a. $S < 0 \ K < 0$ down-facing

$s = -3.84, \ K = -0.03, \ NA = 0.9$

intrinsic loss $\ 0.039$
Results

4b. S<0 K<0 down-facing

$s = -0.25$, $K = -0.988$, $NA = 0.9$

intrinsic loss 3.8%

<table>
<thead>
<tr>
<th>Concentrator</th>
<th>$\theta_s$ (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>Losses for an extended source (equal-étendue designs)</th>
<th>$C/C_{max}$ (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s = -0.25$</td>
<td>5</td>
<td>0.0037</td>
<td>0.08</td>
<td>0.88</td>
</tr>
<tr>
<td>$K = -0.988$</td>
<td>10</td>
<td></td>
<td>0.16</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>0.30</td>
<td>0.66</td>
</tr>
</tbody>
</table>
Results

5. \( S > 0 \) \( K < 0 \) up-facing

- \( s = 0.0445, K = -0.152, NA = 0.9 \) and \( 0.425 \leq \phi \leq \text{ArcSin}(NA) \).
- (a) Full view. (b) Zoom near the focal plane.
- This nominally unfolded design has 21% of the incident rays missing the primary.

<table>
<thead>
<tr>
<th>Concentrator</th>
<th>( \theta_s ) (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>Losses for an extended source (equal-étendue designs)</th>
<th>( C/C_{max} ) (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s = 0.0445 ) ( K = -0.152 )</td>
<td>5</td>
<td>0.21</td>
<td>0.275</td>
<td>0.515</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>0.36</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>0.43</td>
<td>0.36</td>
</tr>
</tbody>
</table>
## Results

### 6. $S>0$ $K<0$ down-facing

$s = 0.19$, $K= -5.22$, $NA = 0.9$

$\pi – \text{ArcSin}(NA) \leq \phi \leq 2.949.$

An intrinsic loss of 4.5%.

<table>
<thead>
<tr>
<th>Concentrator</th>
<th>$\theta_s$ (mrad)</th>
<th>Intrinsic losses (point source)</th>
<th>Losses for an extended source (equal-étendue designs)</th>
<th>$C/C_{max}$ (equal-étendue designs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s = 0.19$</td>
<td>5</td>
<td>0.045</td>
<td>0.03</td>
<td>0.92</td>
</tr>
<tr>
<td>$K= -5.22$</td>
<td>10</td>
<td></td>
<td>0.07</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>0.13</td>
<td>0.82</td>
</tr>
</tbody>
</table>
First-generation unit
SolFocus Inc. USA

31 cm
8 cm
7 kW array
Contracts:
Greece (10MW) and Portugal (8.5 MWp)
Aplanats

Spherical (zeroth-order) aberration
Aplanats

First-order aberration (coma)
$S = -1.25 \quad K = 0.5$
Built-in Quantum Dot Antennas in Dye-Sensitized Solar Cells

Sophia Buhbut, Stella Itzhakov, Dan Oron and Arie Zaban

SSC2010

26-29/4/10
• DSSCs – Background
• Motivation
• FRET – Theory
• FRET in dye sensitized solar cell
• Summery
Dye-sensitized solar cell

- Photon
- Transparent electrode
- $\text{I}^-/\text{I}_3^-$
- Electrolyte
- Nanocrystals of titania coated with dye
- $\text{Ru(ll(bpy)$_2$}^{2+}$
Motivation

• Increased light harvesting in DSSCs
• Photostability – Flexibility – Functionality ?
• Environmental applications.
Forster Resonance Energy Transfer (FRET)

Energy is transfer non-radiativly from an excited fluorophore (donor) to another chromophore (acceptor)

one, which must be fluorescent, is called the **Donor**, and the other, which is not necessarily fluorescent but often is, is called the **Acceptor**.
The mechanism of FRET involves a donor in an excited electronic state, which may transfer its excitation energy to the nearby acceptor in a non-radiative fashion through long-range dipole-dipole interaction.

The theory is based on the concept of treating an excited donor as an oscillating dipole that can undergo an energy exchange with a second dipole having a similar resonance frequency.
Conditions to have some FRET

- Spectral overlap of donor emission spectrum and acceptor excitation spectrum.
- Distance between donor and acceptor should be under 10 nm.
- Electronic dipole orientation between donor and acceptor should be favorable.
In 1948, Förster proposed that

\[ k_T = \frac{1}{\tau_0} \left( \frac{R_0}{R} \right)^6 \left[ \frac{1}{S} \right] \]

The efficiency of energy transfer process varies in proportion to the inverse sixth power of the distance separating the donor and acceptor molecules.
Essential features

In 1948, Förster proposed that

\[ R_0^6 = \frac{9000 \cdot (\ln 10) \cdot \kappa^2 \cdot Q_D \cdot J}{128 \pi^5 n^4 N_{AV}} \]

\[ k_T = \frac{1}{\tau_0} \left( \frac{R_0}{R} \right)^6 \left[ \frac{1}{s} \right] \]

- \( R_0 \) → Forster radius (50% energy transfer)
- \( \tau_0 \) → Average radiative lifetime of the fluorophore
- \( Q \) → Quantum yield of the donor in the absence of acceptor
- \( J \) → Spectral overlap integral
- \( n \) → Refractive index of solvent
- \( K^2 \) → Orientation factor
Essential features

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\[ k_T = \frac{1}{\tau_0} \left( \frac{R_0}{R} \right)^6 \left[ \frac{1}{S} \right] \]

\[ J = \int_0^\infty I_D(\lambda) \varepsilon_A(\lambda) \lambda^4 \, d\lambda \]

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- \( \tau_0 \) → Average radiative lifetime
- \( Q \) → Quantum yield of the donor
- \( J \) → Spectral overlap integral
- \( n \) → Refractive index of solvent
- \( K^2 \) → Orientation factor
FRET in dye sensitized solar cell
Design Rules (donor)

1. Absorb light from 400-800nm.
2. Donors are not involved in charge transfer.

Design Rules (acceptor)

1. Absorb light from 800-1000nm.
2. Strong TiO$_2$ surface adsorption and fast charge injection.
3. Lower recombination rate between electrons in TiO$_2$ and hole in electrolyte.
Energy Transfer (ET) in DSCs

**Electrolyte Quenching**

- Iodine is very mobile (1-5*10^{-5} cm²/s)
- Collisional quencher: PL quenching scale linearly with electrolyte concentration
- High concentration (PMII=0.5M and I₂=0.4M) necessary for DSCs results.

*Nature photonics, 2009,*
Schematic presentation of a system
Proof of concept: QDs with SQ02

CdSe-CdS-ZnS (core-shell-shell)

- Q_D > 70-24%
- No concentration quenching
- Fast emitter (4.8 ns)
- soluble in water (pH=10)

SQ02
unsymmetrical squaraine dye

- ε_{MAX} = 310,000M^{-1} cm^{-1} (at 680 nm)
- Most red shifted sensitizing dye

![chemical structure of SQ02]

5-carboxy-2-((3-(1,3-dihydro-3,3-dimethyl-1-ethyl-2H-indol-2-ylidene)methyl)-2-hydroxy-4-oxo-2-cyclobuten-1-ylidene)methyl)3-3-dimethyl-1-octyl-3H-indolium

---


Proof of concept:
absorption and emission spectra

\[ R_0^6 = \frac{9000 \cdot (\ln 10) \cdot k^2 \cdot Q_D \cdot J}{128\pi^5 n^4 N_{AV}} \]

\[ J = \int_0^\infty I_D(\lambda) \varepsilon_A(\lambda) \lambda^4 d\lambda \]
Electronic mechanism
A band alignment relative to the vacuum level
Proof of concept:
Lifetime measurements

Donor

Normalized intensity

time [ns]
Lifetime measurements

\[ D^* \xrightarrow{K_{\text{FRET}}} A^* \]

\[ D \xleftrightarrow{K_D} D^* \]
Proof of concept: lifetime measurements
FRET effect in cell in presence and absence of acceptor

Donor

Excitation \( \lambda_{EX} = 470[nm] \)

Band-pass filter \( BP = 633 \pm 30[nm] \)
Proof of concept: lifetime measurements

FRET effect in cell in presence and absence of donor

Excitation $\lambda_{EX} = 470[nm]$

long-pass filter $LP = 700[nm]$
Proof of concept:
IPCE measurements
1. A new configuration for dye sensitized solar cells via FRET process.

2. This configuration allows for border spectral absorption for DSSC.

3. FRET efficiency is $E = 44\%$.

4. It opens the way towards the utilization of new materials whose band offsets (relative to the titania electrode) do not allow direct injection.
Recombination Inhibiting Barrier Layer For Type II Dye Sensitized Solar Cells

Idan Hod

Prof. Arie Zaban’s Group
Institute of Nanotechnology and Advanced Materials
Bar-Ilan university

SSC 2010
Outline

• Regular DSSC vs. type II solar cells

• Cell advantages and limitations

• Strategies to overcome limitations

• Results

• Inorganic Hole Extraction Layer for QSSC

• Conclusions
DSSC vs. Type II Solar Cells

Conventional DSSC

- TiO$_2$
- Dye
- Electrolyte

Type II DSSC

- TiO$_2$
- Type II Sensitizer
- Electrolyte

Energy

$E_{CB}$

LUMO

$E_{REDOX}$

HOMO

$E_{VB}$
Dyes having enediol units have been known to bind to the surface of TiO$_2$ through chelation of surface Ti(IV) ions (undercoordinated surface states) with the enediol groups, generally giving rise to very strong DTCT bands.
Type II Dyes

Vial 1: Catechol in Ethanol solution.

Vial 2: Suspension of TiO$_2$ nanoparticle aggregates in ethanol.

Vial 3: TiO$_2$ with Catechol adsorbed to its surface.
Main Advantages

• A cheap replacement for the metal organic dye.

• The possibility to tune the absorption spectrum of the cell.
Tuning the Absorption Spectrum

Metal oxide 1

Metal oxide 2

Metal oxide 3
Limitations

- Not all adsorbed dye inject electrons because charge transfer only occurs when the dye creates a chelating bond on the surface of the TiO$_2$.

- A large portion of the injected electrons recombine back to the oxidized dye molecule (Back Electron Transfer), making it difficult to improve the cell performance (record efficiency less than 1%).
Recombination Inhibiting Barrier Layer

- An electron which was injected into the conduction band of the barrier has a driving force to diffuse to the TiO$_2$ particle (electron transfer 1).

- Forms an energy barrier which prevents recombination of electrons from the conduction band of the TiO$_2$ into oxidized dye (inhibits back electron transfer 2).

SrTiO₃ Barrier Layer

- Dipping a 4 µm thick mesoporous TiO₂ electrode in an ethanolic solution of 1 Mm SrO for different time periods: 45, 90 and 180 seconds.

- Sintering of the electrodes in 550°C for 1h.

- Dipping the electrodes in an ethanolic solution of 10 Mm of dye (Catechol).
Effect of SrTiO$_3$ Barrier Layer

i-V Curve

Best performance was obtained after 90 sec. dipping of SrTiO$_3$ barrier (20% improvement in current).
Effect of SrTiO$_3$ Barrier Layer

IPCE- Incident Photon to Current Efficiency.

Measurements show similar trends as in the i-V curves.
The effect of the coating is better observed when the measured photocurrent is normalized to the amount of effective sensitizer, i.e. Catechol molecules that create a charge transfer complex with the tetrahedral Ti(IV) surface states.

### Table

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>45s dipping</th>
<th>90s dipping</th>
<th>180s dipping</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{sc}$ [mA]</td>
<td>0.418</td>
<td>0.479</td>
<td>0.492</td>
<td>0.473</td>
</tr>
<tr>
<td>Normalized absorption</td>
<td>1.00</td>
<td>0.67</td>
<td>0.82</td>
<td>0.80</td>
</tr>
<tr>
<td>Relative charge collection efficiency ($J_{sc}$/ normalized absorption)</td>
<td>1.00</td>
<td>1.70</td>
<td>1.43</td>
<td>1.42</td>
</tr>
</tbody>
</table>
After laser excitation at 405 nm, the SrTiO₃ coated Catechol sensitized electrode shows slower emission decay compared to the uncoated system, providing strong evidence that the back electron transfer is inhibited by the SrTiO₃ barrier layer.
- Serves as an hole extraction layer for QD’s regeneration.

- Recombination barrier layer.

Inorganic P-type Hole Extraction Layer for QD’s Sensitized Solar Cells
Cell Fabrication

1) **Chemical bath deposition of QD’s**: (example of CdS)

   (1) \( Cd(NTA)_2^{4-} \leftrightarrow Cd(NTA)^- + NTA^{3-} \leftrightarrow Cd^{2+} + 2NTA^{3-} \)
   
   (2) \( Cd^{2+} + 2OH^- \rightarrow Cd(OH)_2(s) \)
   
   (3) \( (NH_2)_2CS + OH^- \rightarrow NCNH_2 + HS^- + H_2O \)
   
   (4) \( NCNH_2 + H_2O \rightarrow (NH_2)_2CO \)
   
   (5) \( Cd(OH)_2(s) + HS^- \rightarrow CdS(s) + OH^- + H_2O \)

2) **Dip coating of NiO**:

   (1) dipping In an aqueous solution of nickel sulfate for 1 hour.
   
   (2) heating to 300°C for 15 min in air.
A combined effect of cell annealing in 300°C and NiO coating resulted in a significant improvement in photo-current.
Cell heating causes aggregation of the QD’s, raising their size and shifting their quantum confinement to the red.
Results: CdS/NiO IPCE and Jsc

NiO1 – 0.2 mM nickel sulfate
NiO2 – 1 mM nickel sulfate
NiO3 – 2 mM nickel sulfate
Conclusions

• A new concept for inhibiting back electron transfer was introduced in the form of an energy barrier layer

• A 20% improvement in cell Photocurrent was obtained by applying a SrTiO$_3$ barrier layer.

• NiO Coating as an Hole Extraction Layer in QSSC significantly improves photocurrent both for CdSe and for CdS.
Thank you for listening
Morphology of ZnO:Sb Nanorods Films deposited by Chemical Bath Deposition

Nir Kedem\textsuperscript{1}, Eran Edri\textsuperscript{1}, Michael Kokotov\textsuperscript{1}, David Ginley\textsuperscript{2} and Gary Hodes\textsuperscript{1}

\textsuperscript{1}. Department of Materials and Interfaces, Weizmann Institute of Science
\textsuperscript{2}. National Renewable Energy Laboratory (NREL)
The Hodes Group – Extremely Thin Absorber Solar Cells

Yafit – TiO2- SbS- CuCNS

Gary

Elena – ZnO- CdS/CdSe - liquid junction

Eran – ZnO- CdS/CdSe- CuCNS

Michael – Development of CBD of ZnO and ZnO-composite films

Nir – Extrinsic doping of ZnO films

Olivia (former student)
Substrate Preparation and Film Deposition

Soda lime glass or FTO-coated glass

Deposition of MnO$_x$ seeds for ZnO nucleation ➔ NOT needed for Sb doped films

Solution composition

Zn$^{2+}$
Sb-tartrate (1% of Zn conc.)
Ethanolamine
Ethylenediamine or Ammonia

PH≈11.2

Kokotov, M.; Hodes, G. J. Mater. Chem. 2009, 19, 3847-3854
ZnO morphology (without Sb)

**Ethylenediamine Bath**

**Ammonia Bath**

Time resolution:
- 5 min
- 10 min
- 20 min
- 30 min
- 40 min
- 60 min

Full thickness after ~60 min.
ZnO:Sb Morphology

Ethylenediamine Bath

Ammonia Bath
ZnO: Sb film, not fully grown

ZnO

ZnO: Sb

Compact layer

Nanorods layer

Substrate
ZnO:Sb Morphology – Retarded rate, two steps growth

Time resolution ——— Full thickness after ~90 min.

Time [min]

Film thickness [μm]

Undoped ZnO

Sb doped ZnO 1

Sb doped ZnO 2

Compact layer
Growth rate ~ 9 nm/min
Final thickness ~ 0.2 μm

Nanorods layer
Growth rate ~ 120 nm/min
Final thickness ~ 3 μm
Sb inhibition of ZnO growth

ZnO over ZnO and ZnO:Sb

Continues growth of nanorods

ZnO:Sb over ZnO and ZnO:Sb

High Sb concentration prevents further growth. Therefore, a new nucleation is required.
## Sb distribution in the film

<table>
<thead>
<tr>
<th>Position</th>
<th>TEM EDS</th>
<th>XPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of nanorods (1)</td>
<td>≈1</td>
<td>1.9</td>
</tr>
<tr>
<td>(2)</td>
<td>2.9</td>
<td>0.4</td>
</tr>
<tr>
<td>(3)</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>6.7</td>
<td>20 - 29</td>
</tr>
<tr>
<td>Compact layer (5)</td>
<td>9.0</td>
<td>8 - 22</td>
</tr>
</tbody>
</table>

Surface enriched with Sb
MnO\(_x\) seeds covers the substrate

Initial nucleation of ZnO

Sb\(_2\)O\(_3\) covers the nuclei, preventing further growth

New nucleation of ZnO takes place

Sb\(_2\)O\(_3\) covers the new layer

After a while a dense film formed

As Sb concentration in the solution drops, nanorods formation begins.

Morphology is still affected by Sb, probably due to preferential adsorption of Sb species on specific ZnO faces.
Substrate “activation” by Sb-rich species

<table>
<thead>
<tr>
<th>Position</th>
<th>XPS</th>
</tr>
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<tbody>
<tr>
<td>Top of nanorods (1)</td>
<td>1.9</td>
</tr>
<tr>
<td>(2)</td>
<td>0.4</td>
</tr>
<tr>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>20 - 29</td>
</tr>
<tr>
<td>Dense layer (5)</td>
<td>8 - 22</td>
</tr>
</tbody>
</table>

A separate activation step is not required. Substrate activation is done *in-situ* by initial deposition of Sb rich layer.
I-V characteristics of the film

ZnO

ZnO:Sb (1%)

ZnO:Sb (0.14%, for solar cell)

Hg droplet contact
Contact diameter ~350μm
Nanorod diameter ~0.2 μm
ZnO/CdS/CuSCN ETA cells

Supporting Glass

Conductive Fluorine doped Sn$_2$O (FTO)

ZnO Nanorod array
Electron conductor

Absorber

CuSCN Hole conductor

Au back-contact
Solar cell performance

Average of eight samples

<table>
<thead>
<tr>
<th></th>
<th>ZnO</th>
<th>ZnO:Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill factor</td>
<td>31%</td>
<td>39%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.16</td>
<td>0.22</td>
</tr>
<tr>
<td>$V_{OC}$ [V]</td>
<td>0.56</td>
<td>0.53</td>
</tr>
<tr>
<td>$I_{SC}$ [mA/cm$^2$]</td>
<td>0.89</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Cell active area of ~1cm$^2$, under illumination of ~1sun
Summary

- Strongly modifies ZnO morphology. Initial layer of highly – compact nanograin is followed by fairly closely packed, flat terminated ZnO nanorods.

- The effect is probably caused by preferential adsorption of Sb-O species on growing ZnO, blocking growth.

- Sb-rich species promote ZnO:Sb nucleation, in-situ, on glass and FTO.

- Reverses diode behavior.

- Vary importantly, ZnO:Sb improves ETA solar cell reproducibility by more efficient blocking layer.

Future work

- Further characterize the electrical properties of ZnO:Sb as deposited and after annealing in various ambient.

- Co-doping with other p-type elements such as Li and N.

- Control ZnO film morphology via other additives.
Thanks

- Dr.Hagai Cohen and Dr.Tatyana Bendikov (XPS)
- Dr.Ronit Popovits-Biro (TEM)
- Dr.Yishay Feldman (XRD)
- Dr.Palle Von huth (FIB)
- Hodes group members

Funding

- U.S-Israel Binational Science Foundation
- Alternative Energy Research Initiative (AERI)

Thank You for your kind attention
HYBRID STRUCTURES OF POROUS SILICON AND CONJUGATED POLYMERS FOR PHOTOVOLTAIC APPLICATIONS

Amit Nahor
Prof. Amir Sa’ar
Racah Institute of Physics and the Center for Nanoscience and Nanotechnology, the Hebrew University of Jerusalem
Outline

- Introduction.
- Porous Silicon (PS)
- Conjugated Polymers
- From DSSC to PS-PVK hybrid structure.
- PVK@PS photovoltaic device.
- Results.
- Conclusions.
Introduction

- **Motivation**
  1. Creating a silicon based cell.
  2. Thin film cell to reduce expenses.

- Our intent is developing a cell which will have a high kwatt/hour to dollar ratio

- We developed a hybrid structure of porous silicon (PS) and conjugated polymers.
  1. high infiltration of the polymer into the PS
  2. high absorption
  3. charge separation
  4. good conductivity.
Porous Silicon

- PS is a sponge-like material.
- PS has a very large surface/volume ratio (up to $500m^2/cm^3$).
- The photovoltaic effect occurs at the interface.
Porous Silicon as a Matrix

Porous Silicon (PS) – an arranged host
Fabrication

Porous silicon by Electrochemical Anodization

Teflon
Si chip
back contact

Hole injection and attack on a Si-H bond by a fluoride ion

Second attack by a fluoride ion with hydrogen evolution and electron injection into the substrate

HF attack to the Si-Si backbonds. The remaining Si surface atoms are bonded to the H atoms and a silicon tetrafluoride molecule is produced

The silicon tetrafluoride reacts with two HF molecules to give $\text{H}_2\text{SiF}_6$ and then ionizes.
Conjugated Polymers

- Conjugated Polymers are polymers which have a single bond and a double bond alternately.
- These electrons are in the $\pi$ band.
- A $\pi \rightarrow \pi^*$ excitation is available in the UV-Visible spectrum.
- Ionizing the Polymer is similar to doping, thus the polymer conducts holes and acts as a P-type SC.

Polyacetylene
From DSSC to PS-PVK hybrid structure
From DSSC to PS-PVK hybrid structure
Polyvinylcarbazole (PVK) Infiltration

- This is a photocconducting polymer which conducts holes and can be referred as a p-type semiconductor.
- Difficult to insert polymers into the PS due to huge aspect ratio.
Cyclic Voltammetry

- We polymerize the monomer inside the pores by using the cyclic voltammetry method.

**PS-PVK Cyclic Voltammetry**

- Oxidation stage
- Monomer oxidation
- Reduction stage
By EDX spectroscopy we can identify the different elements and know whether the polymer has been inserted into the PS.
After inserting the PVK into the PS we have added top contacts.

We have tried a wide variety of contacts and have resolved that our best results are from Au thin films.
Results

IV Curves of PS-PVK Hybrid Structure

Isc = 1.3 mA/cm^2
Voc = 151 mV
Results

- Our cell efficiency isn’t good enough.
- PVK is not the best polymer for the job:
  1. Branching during the polymerization causes a decrease in conductivity.
  2. PVK absorption spectrum isn’t suitable for photovoltaic application.
Conclusions

- We have shown the feasibility of a photovoltaic cell based on PS and PVK hybrid structure.
- We have shown we can insert polymers into the PS matrix using the CV method.
- Future work: using more adequate polymers and inserting nanoparticles.
Acknowledgements

Prof. Amir Sa’ar
Oren Berger
Racah Institute of Physics and the Center for Nanoscience and Nanotechnology, the Hebrew University of Jerusalem

Prof. Micha Asscher
Gil Toker
Department of Chemistry and the Center for Nanoscience and Nanotechnology, the Hebrew University of Jerusalem

Prof. Shlomo Yitzchaik
Yoseph Bar-David
Yair Tamar
Leah Reiss
Department of Chemistry and the Center for Nanoscience and Nanotechnology, the Hebrew University of Jerusalem
Thank you very much for your attention
Improving the utility of existing solar arrays

A presentation by Yotam Frechter

Supervisor: Prof. Raul Rabinovici

Dept. of Electrical & Computer Engineering, Ben Gurion University of the Negev
Partial shading of a solar array
Problem and solutions

- The solutions offered today are not satisfactory. Even with the best MPPT, as long as the cells are not connected in the ideal fashion, a part of the sun’s energy is simply not gathered from them, resulting in heat.

- Counter-measures include mainly blocking diodes and bypass diodes.

- Blocking diodes simply disconnect (in the worst scenario) an entire string of cells and then all of its energy is lost.

- Bypass diodes, simply bypass weak cells so again, only the bypassed cell’s energy is lost – which still a loss.

- Therefore, a controller which can connect the cells differently and better, can improve the array’s output even if the array is equipped both with bypass and blocking diodes.
A short explanation about bypass and blocking diodes

- A common way to deal with the breakdown current or block it completely is to put either a bypass diode which opens in a lower voltage than the cell breaks, or a blocking diode on the entire string of cells. This is how these topologies look:
The effects of bypass and blocking diodes

- Even though blocking diodes lower the output voltage in about 0.7V, at least they block the breakdown current entirely. But, this achievement comes at the price of the disconnection of an entire string. That is why these diodes are unpopular in the design and used only when necessary.

- Bypass diodes, on the other side, protect the panels from hotspots (when partial shading turns cells to a load on the entire array) while allowing the utilization of the rest of the array, as the diode itself being a very small load on the array. This is why these diodes are extremely common and appear in virtually any modern panel design.

- Bypass diodes influence shall be investigated and their protection on the cells demonstrated, however it shall also be demonstrated that they do not really help improve the array’s utility, if the work point can be checked.
Simulation: the effect of a bypass diode on a single cell

- It is quite easy to understand the effect of a bypass diode: it bypasses completely the cell the moment its voltage drops below the forward voltage of the diode. It opens thus protect the cell from overheating as all the current goes through the diode and not through the cell, where in a real situation, the cell current actually drops a little when it opens even as the voltage rises.

- A bypass diode has a meaningless influence on the forward voltage of the cell in normal operation mode.

- Diodes where modeled with a forward voltage of 0.7V. The cell’s breakdown voltage is 1V:

![IV Curves](image_url)
Even with a bypass diode which breaks in a minimal voltage, the output only gets close to the maximal possible but never reaches it.

An additional local maxima is produced on the power curve.

The maximal power is not necessarily received in the lobe which the diode adds. In other words, if the working point can be moved, than the diode is redundant.

In fact, since on a shaded cell there will always be a reverse voltage, taking both the faulty cell and the diode away, is the ideal bypass diode for any practical purposes.

Simulation: The effect of the bypass diode on 3 cells which are connected in series to a partially shaded cell for different values of $v_f$.
How can the working point of the cells be moved to the optimum?

- If one knows where the MPP of each and every cell is, than the cells can be sorted by it and arranged from best to worst. Than, the following arrangement ensures an identical number of S remaining weakest cells are always connected to S remaining strongest cells, in parallel.

  - This gives a connection scheme with N blocks, each with P strings.
  - This method is called “Meandering”.
  - But how can the MPP of each cell be foreseen?
The 10 parameter model

- This model describes the behavior of a solar cell
  - For a general cell, it looks like this:

![Diagram of a general solar cell model](attachment:image.png)

- A possible model for a DSSC cell would be:

![Diagram of a DSSC cell model](attachment:image.png)

- There is no validated model for a DSSC cell yet.
The mathematical model

A mathematical model for solar cells

- For the general cell, the 10-parameter model turns to

\[
I = I_{ph} - I_0 \left( e^{(V+I\cdot R_s)/V_T n_1} - 1 \right) - I_0 \left( e^{(V+I\cdot R_s)/V_T n_2} - 1 \right) - \frac{V + I \cdot R_s}{R_{sh}} - \alpha \frac{V + I \cdot R_s}{R_{sh}} \left( 1 - \frac{V + I \cdot R_s}{V_{br}} \right)^{-m}
\]

- For a DSSC cell, the model could be

\[
I = I_{ph} - I_0 \left( e^{(V+I\cdot R_s)/V_T n} - 1 \right) - \frac{V + I \cdot R_s}{R_{sh}} - \alpha \frac{V + I \cdot R_s}{R_{sh}} \left( 1 - \frac{V + I \cdot R_s}{V_{br}} \right)^{-m}
\]

- There is no solid model for the breakdown of DSSC cells. In fact, these cells may even be bi-directional up to a certain criterion (Prof. Arie Zaban conjecture).
Temperature dependence

- There’s a direct connection between the diodes saturation currents and the cell’s temperature, by the following equations (for silicon cells)

\[
I_{0_1}(T_1) = I_{0_1}(T_0) \cdot \left( \frac{T_1}{T_0} \right)^3 \cdot 1.3 \times 10^4 \left( \frac{1}{T_0} - \frac{1}{T_1} \right)
\]

\[
I_{0_2}(T_1) = I_{0_2}(T_0) \cdot \left( \frac{T_1}{T_0} \right)^{3/2} \cdot 0.65 \times 10^4 \left( \frac{1}{T_0} - \frac{1}{T_1} \right)
\]

\[
I_{sc}(T_1) = I_{sc}(T_0) + \alpha_1(T_1 - T_0)
\]

- If the current is known and the temperature is also known, \(I_{sc}\) can be deduced and therefore also the illumination level can be deduced.

- Even if the temperature is not exactly known, it can be deduced from the cell’s voltage and current by an iterative process which converges on most cases and if it does not converge, still, a single temperature measure on any cell in the array can be taken since this will not deviate much between cells who are assumed to be working properly (right up to the measurement moment).

- Since for each illumination level the cell’s curves are distinct, then from this, all of the cell power curve may be deduced, if all cell parameters are known.
Curves in different illumination levels – are distinct

Curves in different temperatures have only one bisection point
Therefore, if exact parameters are known for a solar cell, and basic wind and temperature to begin iterations are also known, both the illumination and the exact temperature can be deduced out of a single current and voltage measurement, at the cell’s current working point.

This is so since the I/V Curves of the cell for a known temperature, are distinct.

And this means that the entire power curve of the cell can be deduced from a single measurement and known parameters.

To perform this feat, one needs to do periodic measurements of the parameters.
Why is a single measurement important?

- Most system in the market today who do change cell interconnection, are searching for the optimum state using generic algorithms like uphill/quasi-newton. These algorithms are forcing the system to disconnect parts of the array and reconnect them to known loads for several milliseconds each time. This is called “Experimental” or “Try and Check MPPT.”

- It can be shown that a single measurement is sufficient in the present working point and then the disconnections/reconnections are redundant. Hall sensors and voltage sensors (or connection points for a controller) are sufficient to control the entire array. This measurement will already enable the controller to calculate approximated curves and MPPs.
This outcome can be used to deduce the MPP of every cell or group of cell in the array and then the controller can select the best interconnection by meandering that will move the working point of every panel/cell close to its MPP. The rest of the tracking can be completed by the array’s inverter. This way, the MPPT unit is redundant.

This is important for large and very large arrays where the MPPT unit which is a DC/DC converter, is very expensive, while the inverter may be electromechanical, which is easily controlled.
A single cell simulation in detail

- The simulation was performed in Matlab/Simulink
Inside the solar cell block

- The 10-parameter model equation is inside the blue model block.
An entire array simulation

- Single cell in different Illuminations:

- Since the curves drop to 0 voltage in different currents, a backward breakdown is possible.
Consequences of series connection

- A series connection may create different local MPPs. Here the simulation is on a series connection of 10 full illuminated cells (1 Sun), 2 2/3 Sun illuminated cells and 3 1/3 illuminated cells.

- A local MPP is resulting around 0.8A and much power would be lost by a MPPT which get stuck in it, until the partial shading ends (if it's not caused by faulty cells which could remain like this).
Maximal efficiency of the array

- Had the cells been connected with a small MPPT unit each, than this is what would have been received in the ideal case.

- A lot have been lost during shading, as 15W could have been scooped of the array but only 7.2W were actually recovered.

- The solution of connecting a MPPT to each panel is not an economically feasible solution for very large solar arrays.
Near-Optimal: 3-Strings Meandering

- Another solution is shown here: much of the problem is removed by even just partial meandering. To do it, of course, one has to estimate the panels MPPs.
Comparison to bypass diodes

- It is quite easy to show bypass diodes are not a very successful solution.

- In cyan, the model is run with “Ideal Bypass” which means simply without the faulty cells.

- If near-optimal meandering used, than the diodes are redundant and the output is about 10% larger, as shown by the red curve.
The Goal

- To produce a controller which would sample voltage and current on central groups of panels in a field to perform the I/V curve estimation for each group online.
- The controller can then use meandering to design an interconnection scheme which will improve the field utility.
- By a finite interconnection matrix and number of spare power lines, this controller would be able to improve the performance online, the accuracy only limited by the resolution of the curve estimate and number of available power lines.
- The array’s output would pass a single MPPT – where the array’s inverter could also function as one, instead of individual MPPT units for the panels.
- Near optimal output is attainable.
- This result is relevant for every silicon solar cell in the market today, including monocrystalline, polycrystalline and nanocrystalline cells.
- It can be adapted to other kinds of solar cells, by changing the model.
Disadvantages

- The need to know as precisely as possible all parameters of each panel group. This enforces monthly measurements and online corrections.

- There is a trade-off here: the number of sniffing connections/disconnections is cut to zero, at the expense of computational power.

- The only connections/disconnections that will remain are the changes of state of the interconnection matrix, when necessary.

- This may still not as good as a MPPT for each panel. But this solution is not economical for large fields.
Advantages

- Possible improvement of tens of percentages in the output when partial shading is present, in relation to working without any protection.
- Relatively cheap solution. The only cost is the interconnection matrix, spare cables and controller while the MPPT unit usually costs more in itself.
- Online measurements can also be used to predict and alarm about degradation of panels (not to mention, panel theft).
- This result can be adapted to commercial use.
Partial material cost estimate for a 50KW solar array upgrade


b. Assuming field is composed from 120 panels, complete sort meandering would require at least 829 double-connection relays at 4$ each for the sorting connection matrix. However, this estimate could be reduced greatly by using partial meandering on larger groups of cells. E.G by dividing to 30 groups of four panels each, this could be lowered to as few as 148 double-connected Relays at 4$ each. A reasonable estimate would be about 240 Relays overall.

c. Added cables will cost at least another 4$ each from the connection matrix to the panels.

d. This gives a total raw cost of 110+240*(4+2)=1550$. However, Most of the cost would be the work hours necessary to upgrade and the microcontroller's programming and not the raw material cost. So this is a low end estimate. Also, Hall sensors prices have not been included here.
Future study

- Efficient software/algorithmt to manage solar arrays using a PLC to control the array, by the illumination over the cells.
- Characterization of different kinds of cells.
- Similar methods for wind turbine fields, especially for small turbines where the wind speed is relatively low.
- A smart controller which can supervise both solar panels and wind turbines and which will also be able to alert maintenance, whenever necessary.
5. Liyuan Han, Naoki Koide, Yasuo Chiba, Takehito Mitate, “Modeling of an equivalent circuit for dye-sensitized solar cells”, APPLIED PHYSICS LETTERS, Vol. 84, pages 2433-243
Questions?