Optimal Design of Renewable Based Mini-grid Systems – Opportunities and Challenges

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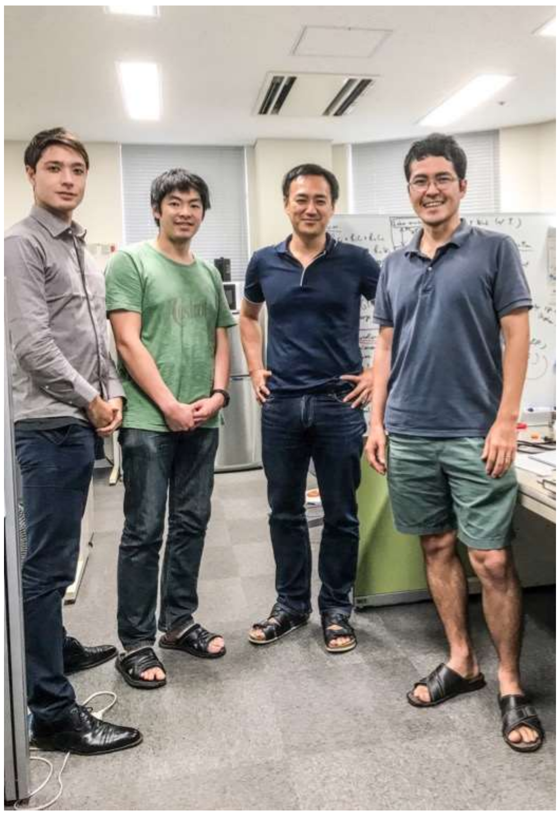
- Itoshima Mini-hydro Energy Co., Ltd (Founder)

【 Self-introduction 】

Technology and Policy Department of Urban and environmental Engineering, Kyushu University - Assistant Professor

Urban Institute

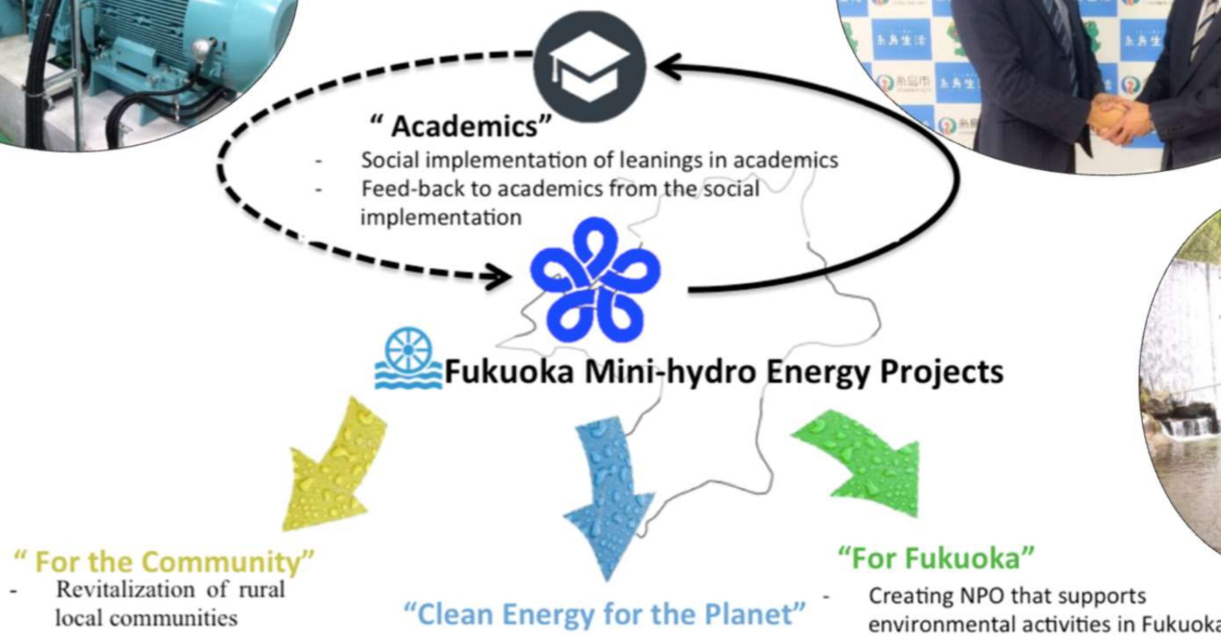


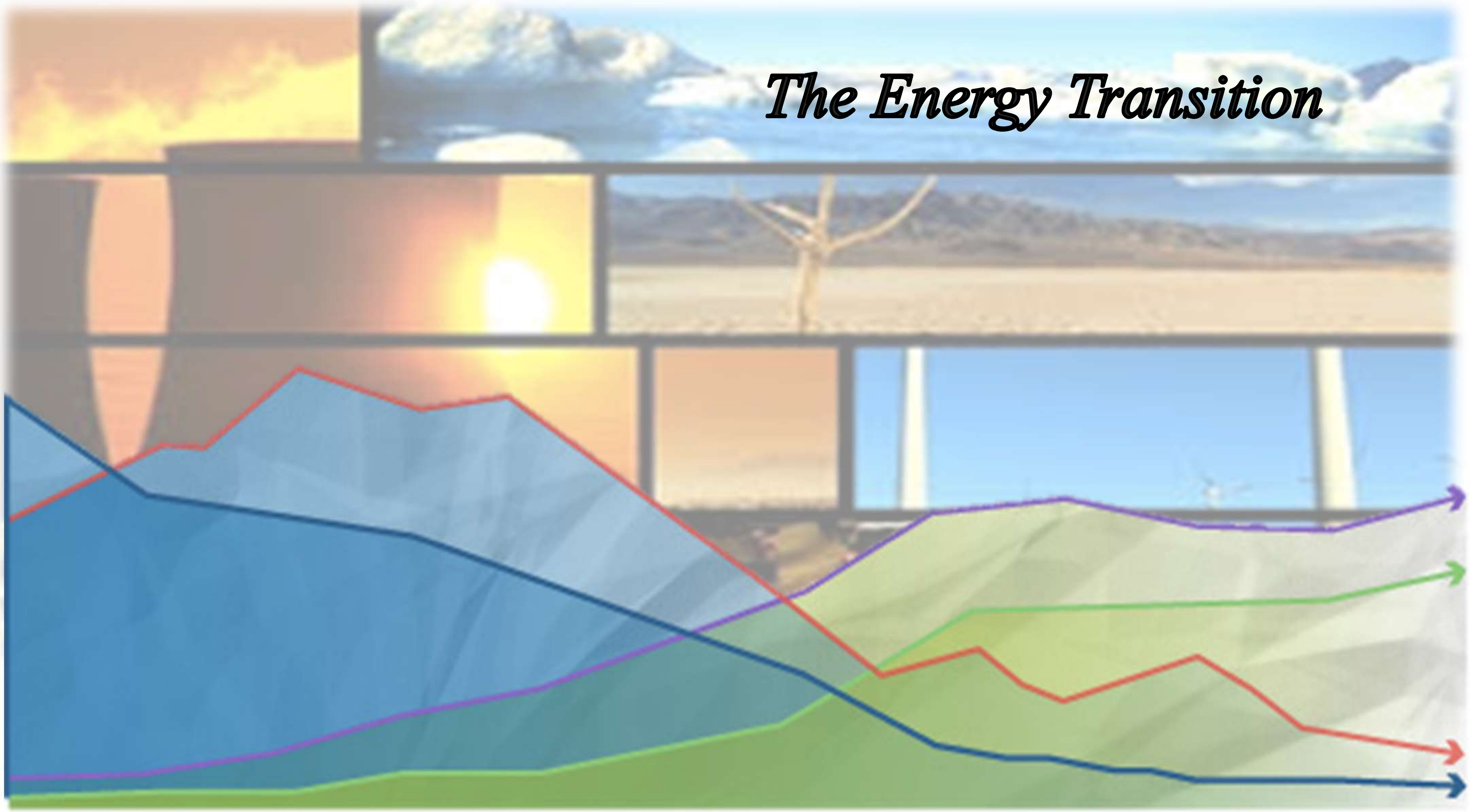
Field of Specialization :
Environmental Economics; International Economics; Energy Economics
Special Interests :
Economic Policies; Renewable Energy; Finance and Investment

- Working on:
  Energy Market Analysis; Impact Assessment of RE Project; Inclusive Wealth Index

【Self-introduction】

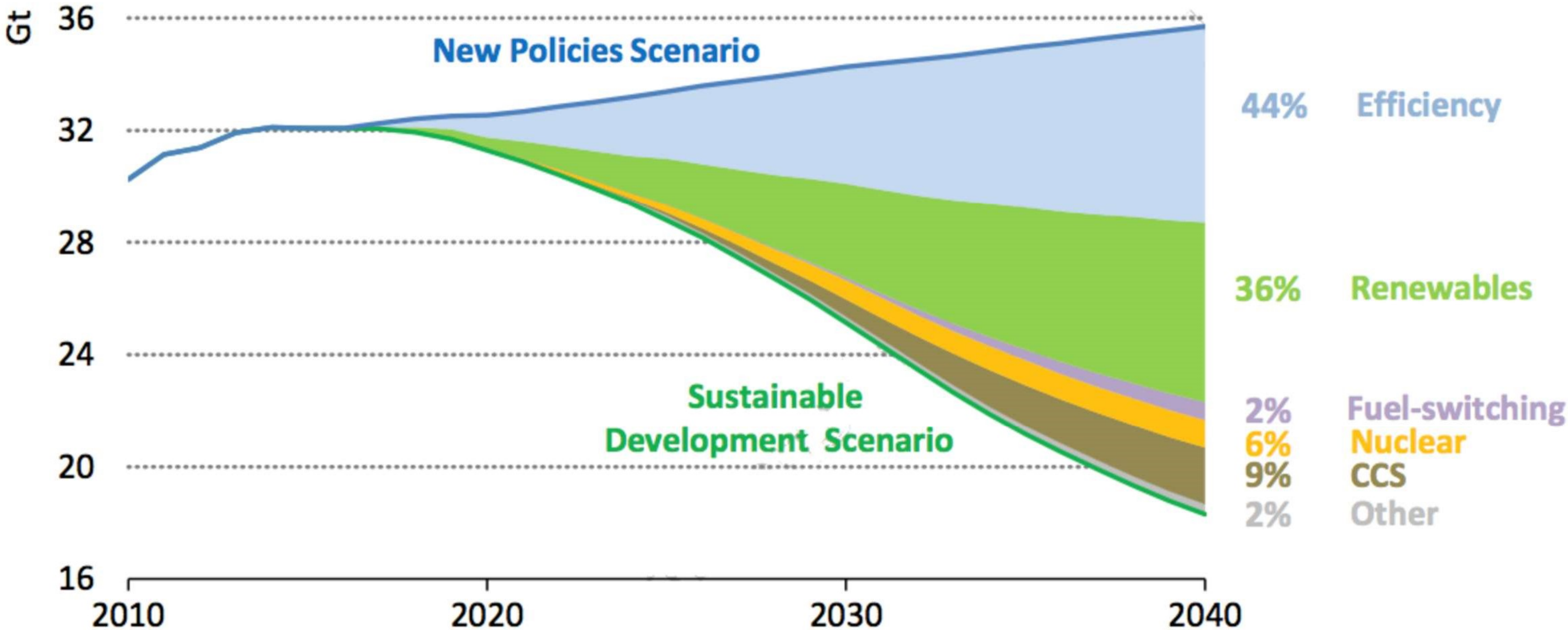
Itoshima Mini-hydro Energy Co., Ltd - Founder (2016)




The Energy Transition

【Background】

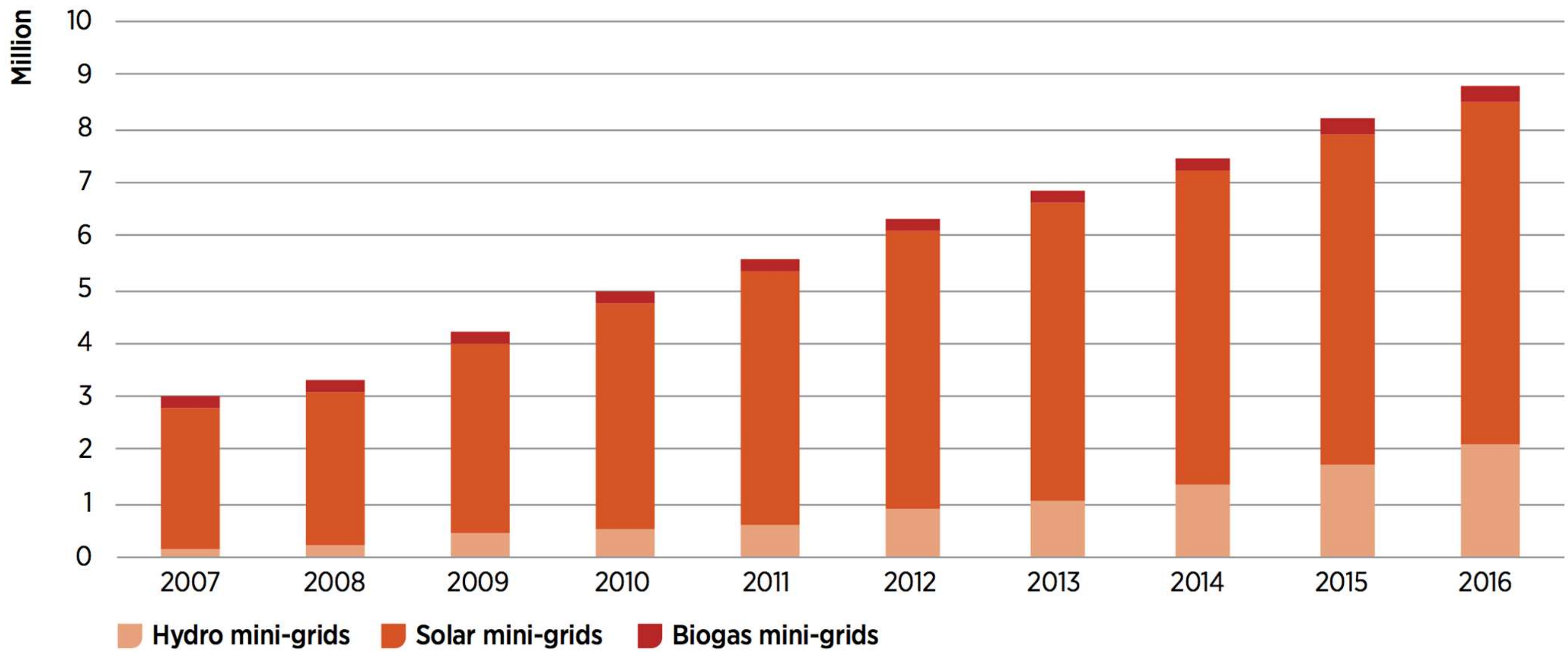
Driverts of the reduction in CO2 emissions to meet the 2C warming limit



Source: IEA, 2017: WEO2017

【Background】

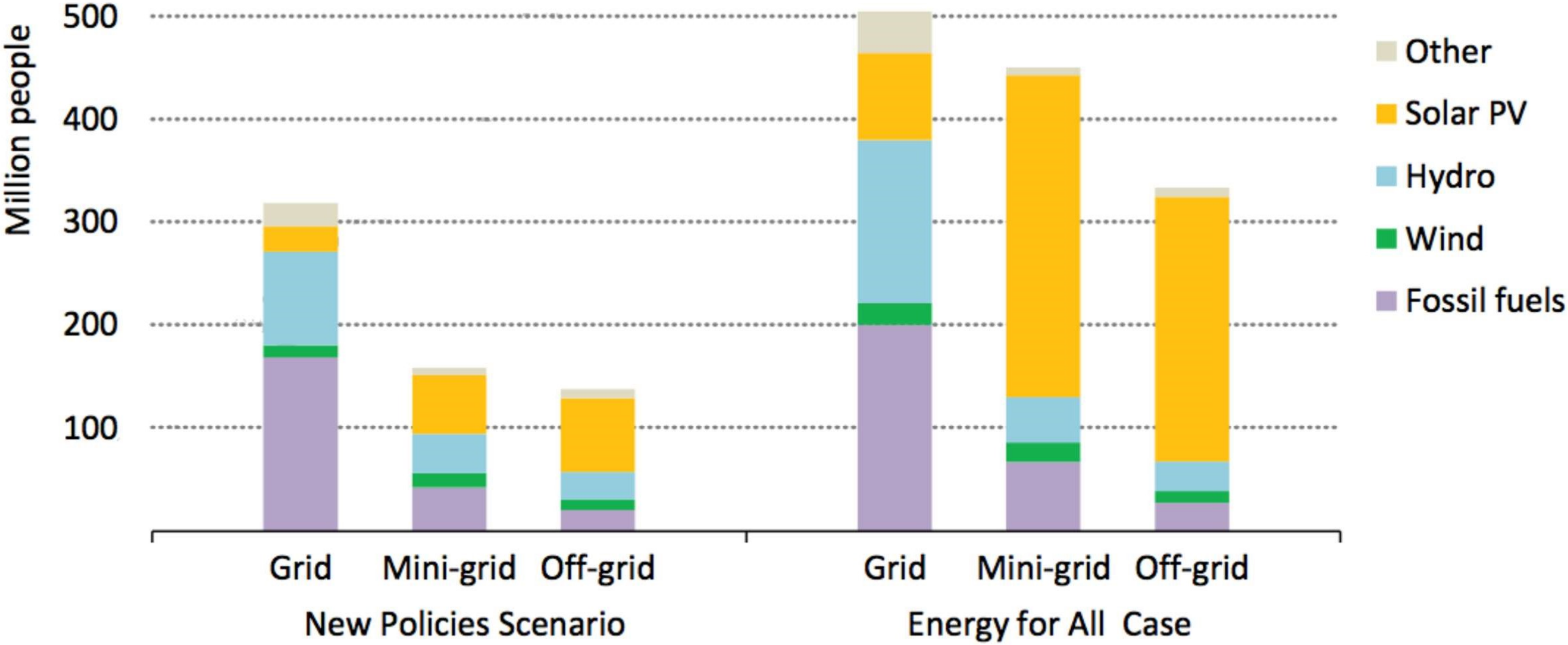
Number of people connected to renewable energy mini-grids by technology (2007-2016)



Source: IRENA, 2018

【Background】

Population gaining access to electricity by scenario (2017 - 2030)



Source: IEA, 2017: WEO2017

* <u>"Energy for All Case" would cost a total of around $800bn</u>

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- **Optimal design of renewable based mini-grid systems**

Method: LCOE (Levelized cost of energy) analysis

1) The case of Indonesia

- Comparison between Solar PV Hybrid (with Diesel) and Diesel based mini-grid systems

2) The case of Myanmar

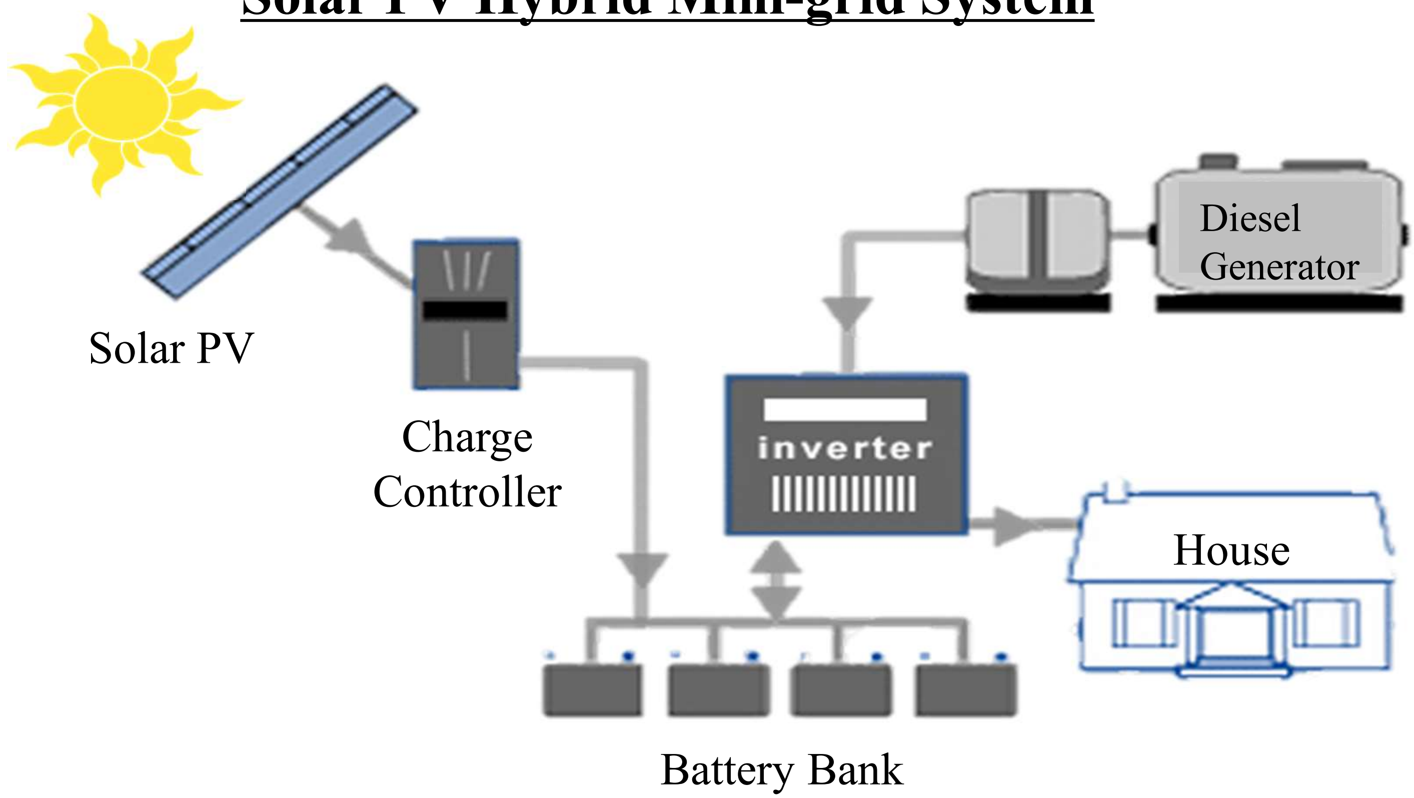
- Comparison between 100% Renewable Hybrid (Solar PV and Wind) and Diesel based mini-grid systems

- **DRM measures for Resilient Mini-grid Systems**

Optimal design of renewable based mini-grid systems LCOE analysis: ***Indonesia***

【1 – Indonesia】

Solar PV Hybrid Mini-grid System



Question:

1) Are Solar PV Hybrid Mini-grid Systems economically viable compared to conventional Diesel Systems?
2) Can Solar PV Hybrid Mini-grid Systems attract private investments?

Optimal design of renewable based mini-grid systems

LCOE analysis: *Indonesia*

Key Takeaways:

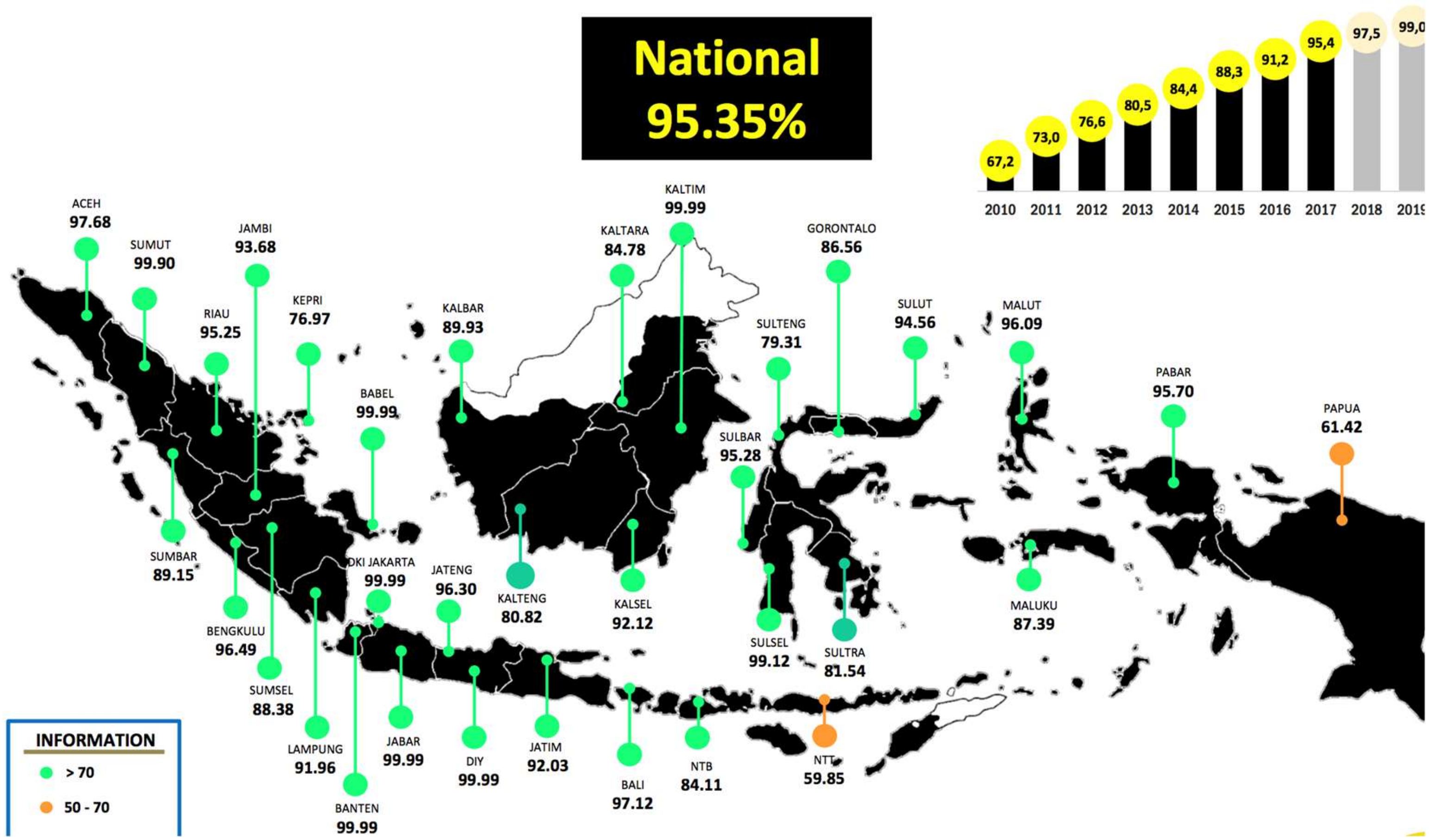
I. Compared to conventional Diesel systems, LCOE of **Solar PV Hybrid system** is **lower even under the most conservative case with 100% equity financing** (WACC:14.34%)

II. The **Solar PV Hybrid system becomes financially viable** with **grant finance that covers around 1/3 of the total cost**

III. **Pure equity financing greatly reduces the financial viability of the investment** compared to that of D/E of 4, 1, which highlights the importance of **access to low-cost finance for attracting private investments**

【1 – Indonesia】

- 95% electrification rate, with a total installed capacity of 61 GW (as of 2017)
- 10 million people still lack access to electricity most of whom reside in extremely remote villages



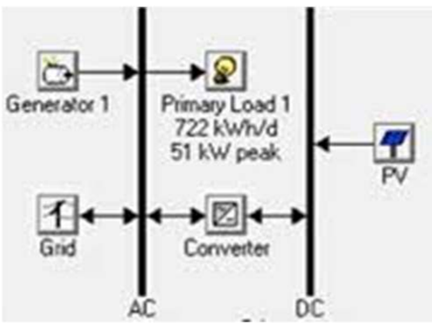
Source: MEMR, 2018

【1 – Indonesia】

Methods

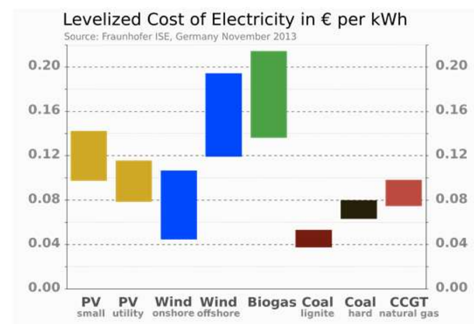
(1) Compare Levelized cost of energy (LCOE) of the two Systems: Renewable Hybrid Mini-grid Systems and Diesel Mini-grid Systems

a) Build Optimized Mini-grid systems using HOMER



b) Calculate weighted average cost of capital (WACC) for three different financing scenarios: Debt/Equity Ratio 4, 1, 100% Equity

c) Calculate LCOE of both systems and compare



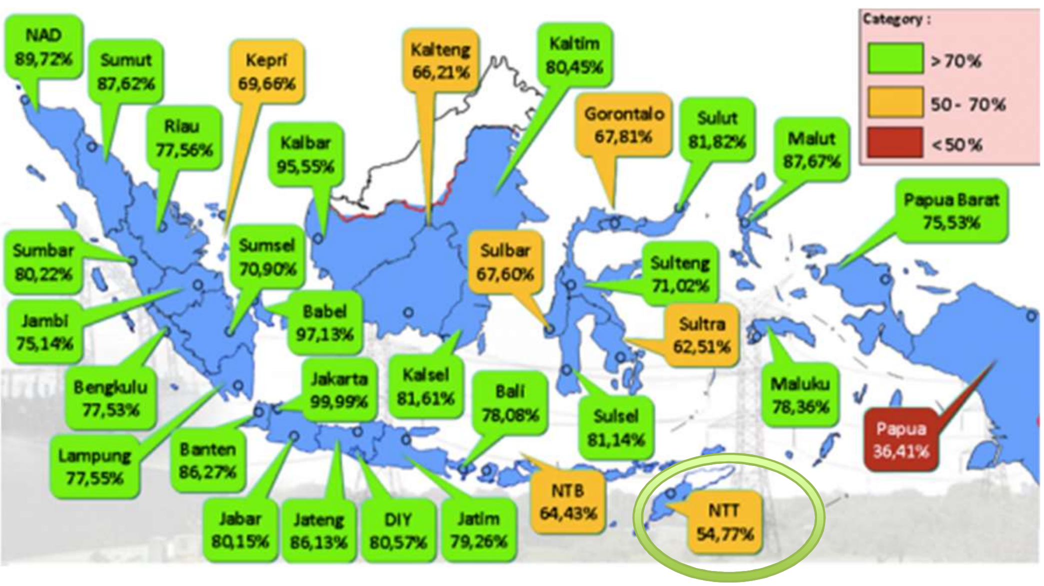
(2) Analyze Internal Rate of Return (IRR) and Net Present Value (NPV) of the Hybrid Systems

a) Calculate IRR and NPV with different grant ratio: from 0% up to 50%

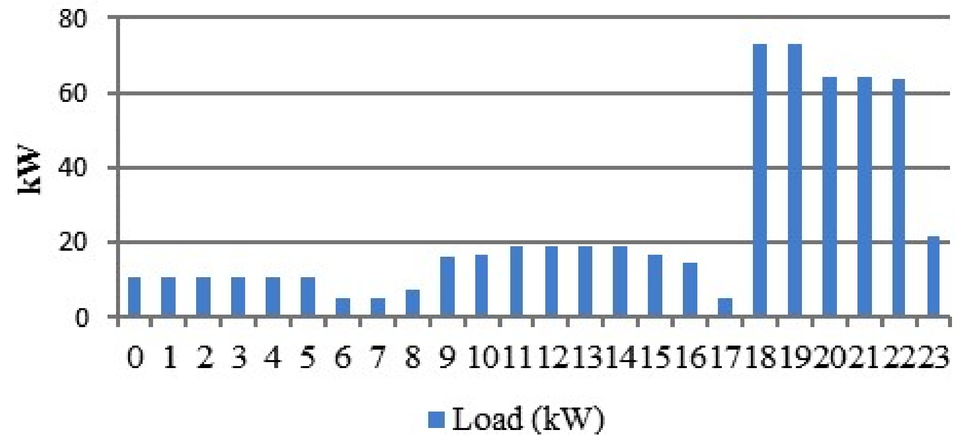
【1 – Indonesia】

Data

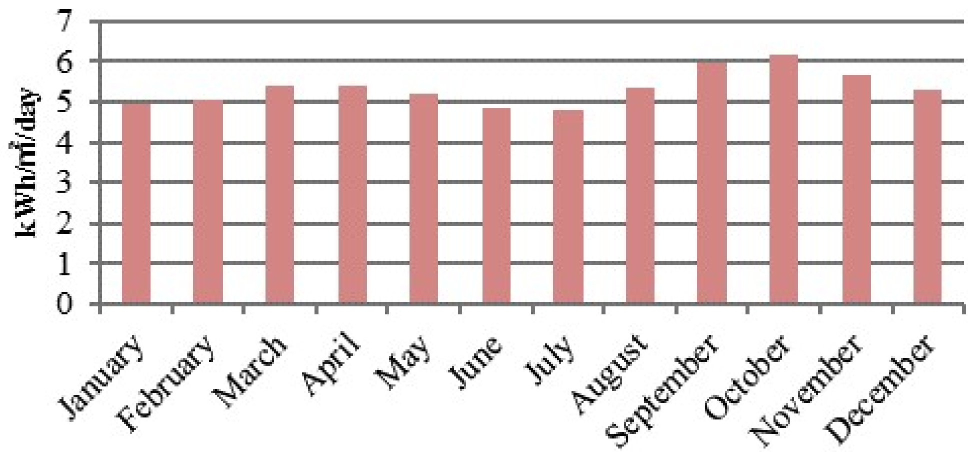
A generic village with 1,475 people in 350 households in Nusa Tenggara Timur (NTT) is chosen as an assumed project site



Electricity demand profile of the generic village



Renewable Resources:
Solar Irradiance at the assumed project site



Source: NASA Surface Meteorology and Solar Energy database

【1 – Indonesia】

Data

Average component prices and O&M costs for solar PV, batteries, converters, and grid networks in Indonesia

Components	System Cost	O&M Cost	Replacement Cost
Solar PV	US$2,100/kW to US$3,150/kW	US$19/yr/kW	-
Batteries	US$180/unit to US$270/unit (1kWh generic Lead Acid Battery)	US$10/yr/unit	US$150/unit to US$225/unit
Converters	US$900/kW to US$1,350/kW	US$7.8/yr/kW	US$800/kW to US$1,200/kW
Diesel Generators	US$650/kW	US$0.05/hr/kW	US$650/kW
Transmission Infrastructure	US$2,000/km	US$160/yr/km	-
Fuel Cost	$0.5007/litter to $1.367/litter	-	-

provided by the Ministry of Energy and Mineral Resources of the Republic of Indonesia in June, 2016

Summary of Inputs for Calculation of WACC

Risk Free Rate	7.62%[a]
Market Risk Premium	8.0%[b]
Beta	0.84[c]
Cost of Equity	14.34%
Cost of Debt	12.27%
Corporate Tax Rate	25%

[a] Based on Indonesia Government Bond 10Y (as of April 2016), [c] Calculated based on the Risk Free Rate and the Market Risk Premium

【1 – Indonesia】

Results

(1) LCOE of Renewable Hybrid Mini-grid Systems and Diesel Mini-grid Systems

WACC for three different scenarios

D/E Ratio	WACC
4	10.23%
1	11.77%
100% Equity	14.34%

LCOE in the reference case (11.77%)

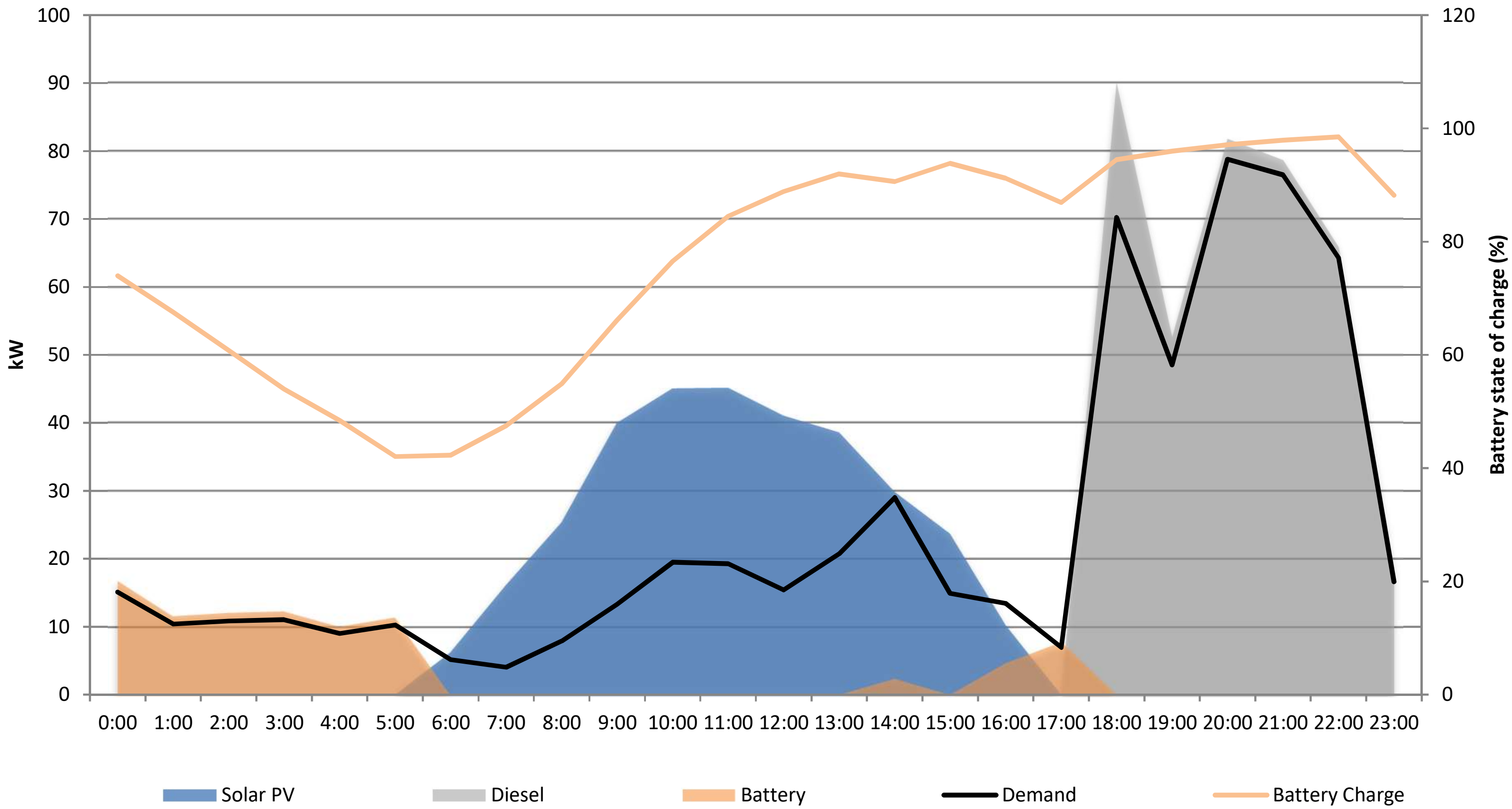
System	Composition		LCOE
Renewable Hybrid Mini-grid system	Solar PV	60kw	$0.57
	Diesel Generator	140kw	
	1kwh Lead Acid Battery	200 strings	
	System Converter	30 kw	
	Transmission Infrastructure	3.5km	
Diesel Mini-grid system	Diesel Generator	140kw	$0.60
	Diesel Generator	30kw	
	Transmission Infrastructure	3.5km	

【1 – Indonesia】

Results

(1) LCOE of Renewable Hybrid Mini-grid Systems and Diesel Mini-grid Systems

How demand is met with Renewable Hybrid Mini-grid System



60kw of Solar PV:

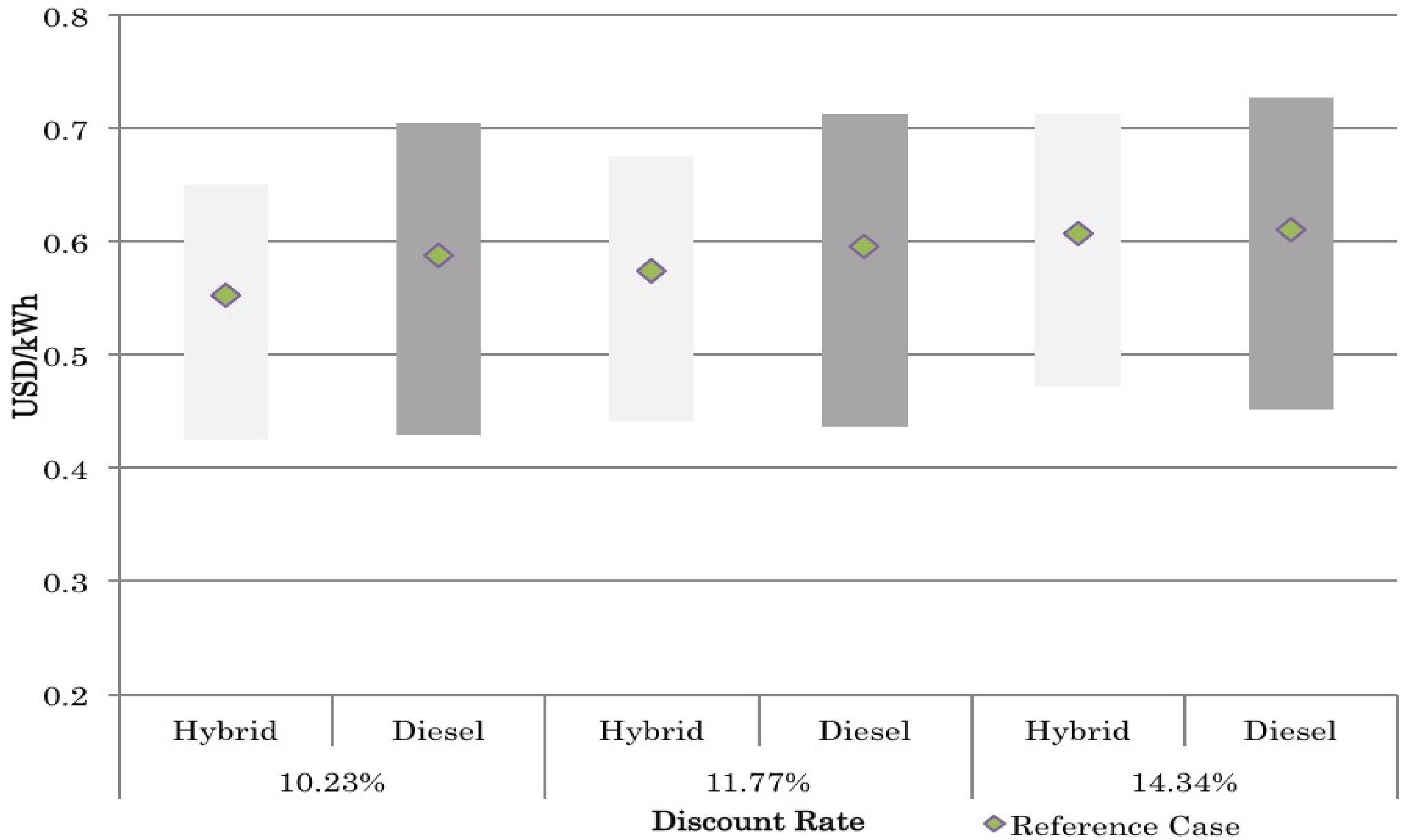
- Provides over 40% of the total generation
- Cuts CO_2 emission by approximately 66% over the 25 year lifetime of the system.

【1 – Indonesia】

Results

(1) LCOE of Renewable Hybrid Mini-grid Systems and Diesel Mini-grid Systems

In the reference cases, LCOE of **Hybrid Systems** is **lower even under the most conservative case with 100% equity financing** (WACC:14.34%)

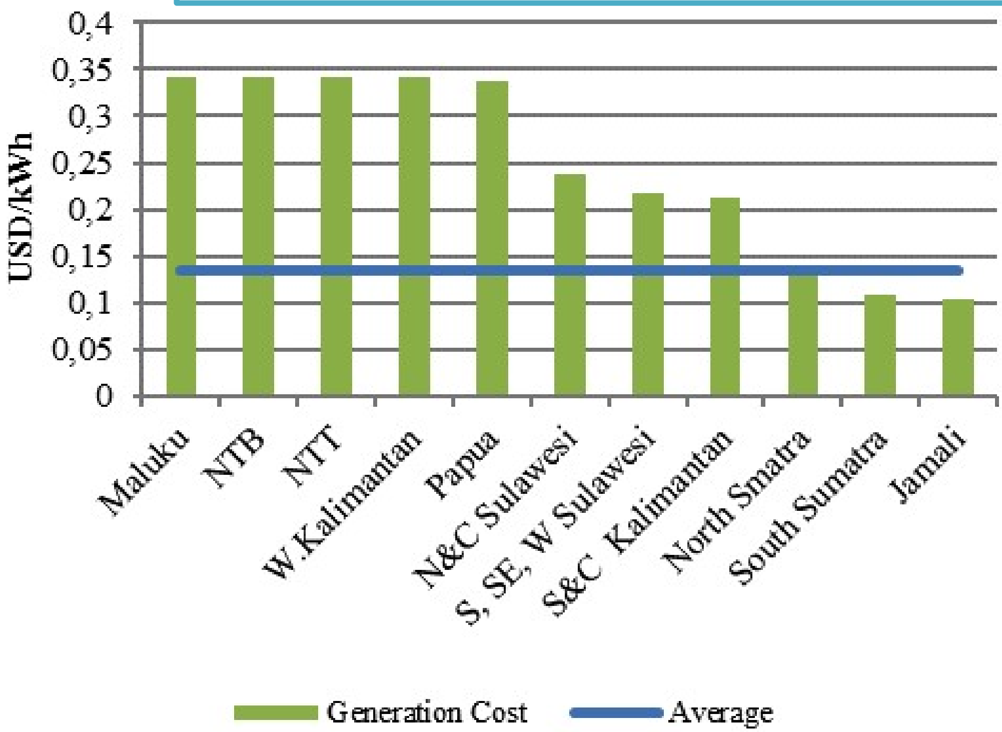


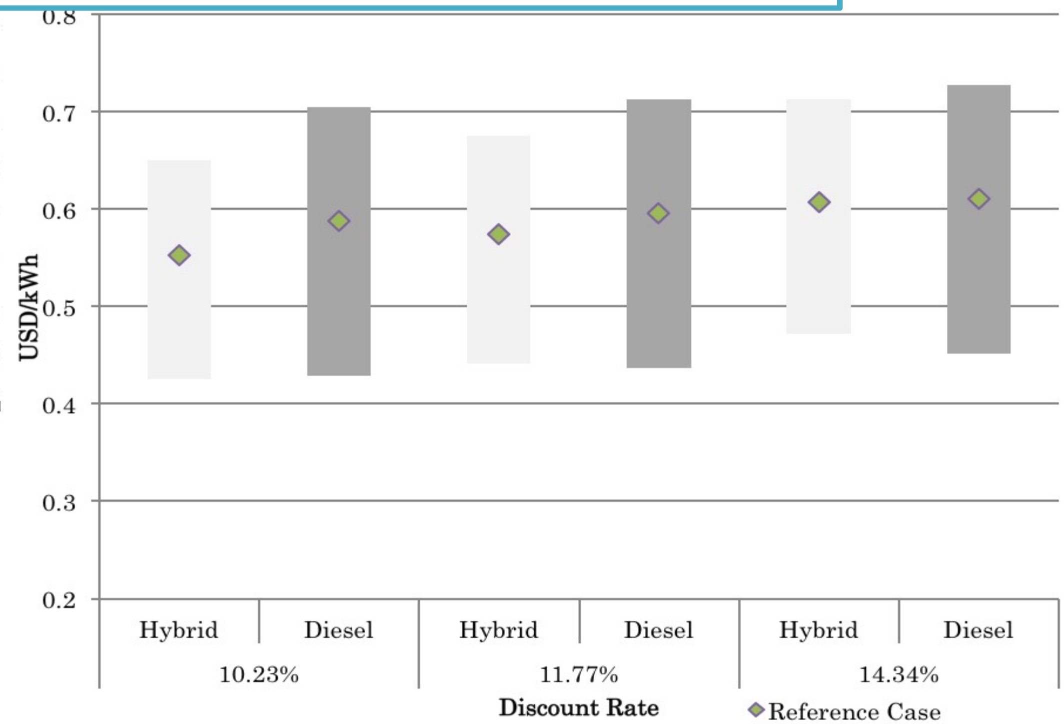
【1 – Indonesia】

Results

(1) LCOE of Renewable Hybrid Mini-grid Systems and Diesel Mini-grid Systems

However, the LCOE of the Hybrid system is still higher than the national grid generation cost: USD 0.34/kWh





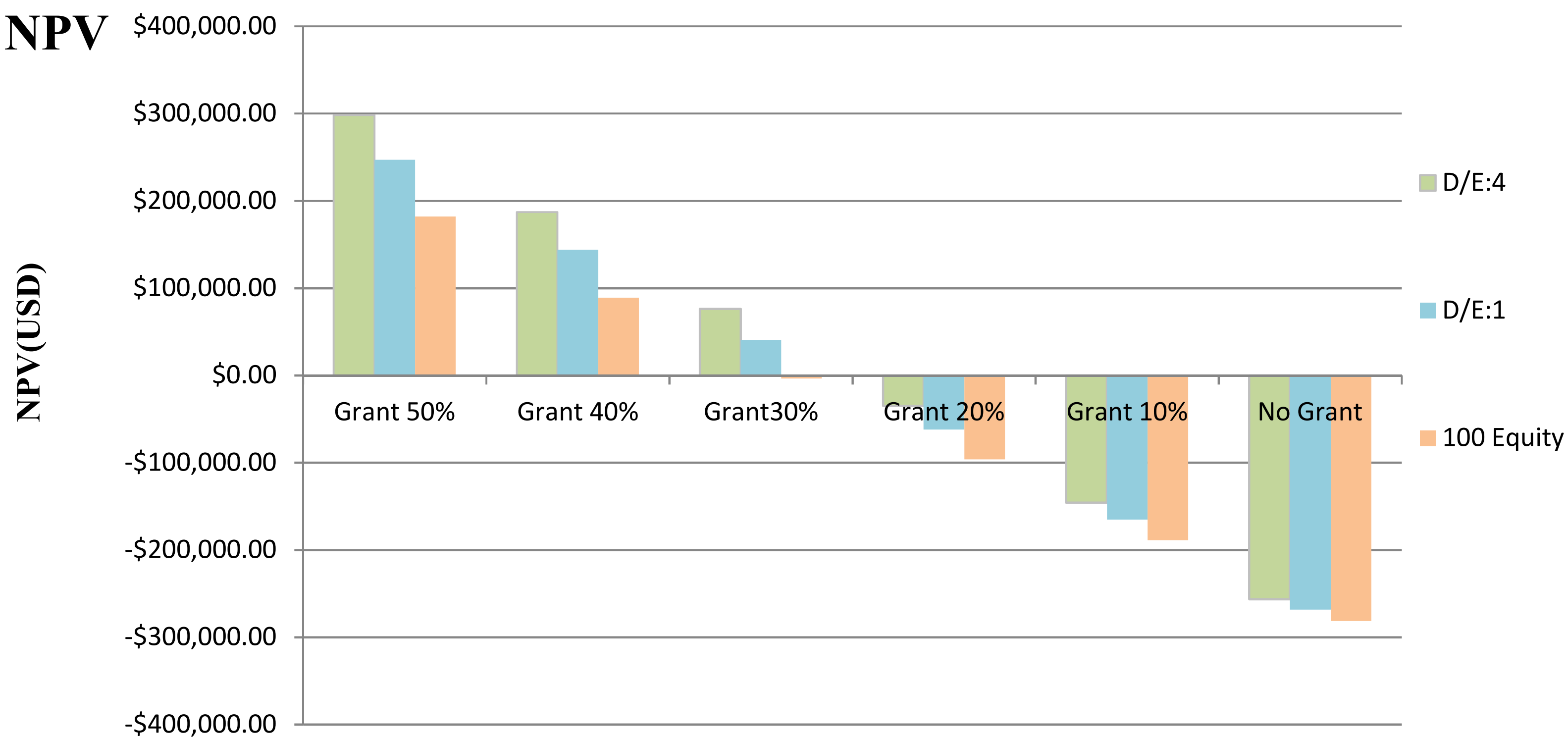
Results

(2) Analyze IRR and NPV of the Hybrid Systems

Three financing scenarios are examined: **D/E of 4, 1, and 100% equity**, with **grant finance ranging from 0% to 50%** of the total cost of the project

Pure equity financing greatly reduces the financial viability of the investment

With around 35% of grant, the project is financially viable in all scenarios



【1 – Indonesia】

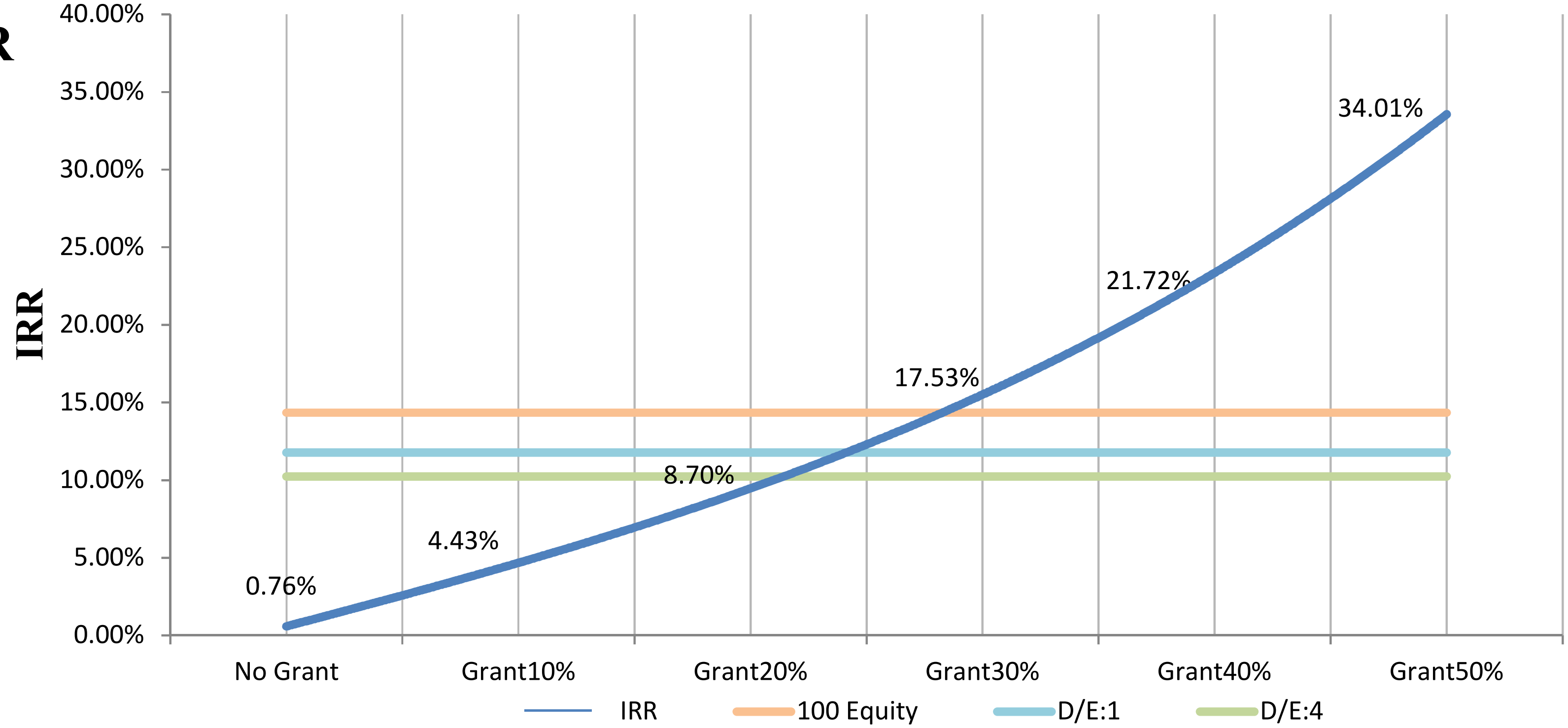
Results

(2) Analyze IRR and NPV of the Hybrid Systems

Three financing scenarios are examined: **D/E of 4, 1, and 100% equity**, with **grant finance ranging from 0% to 50%** of the total cost of the project

With around 35% of grant, the IRR of the project is higher than the WACC of all scenarios

IRR



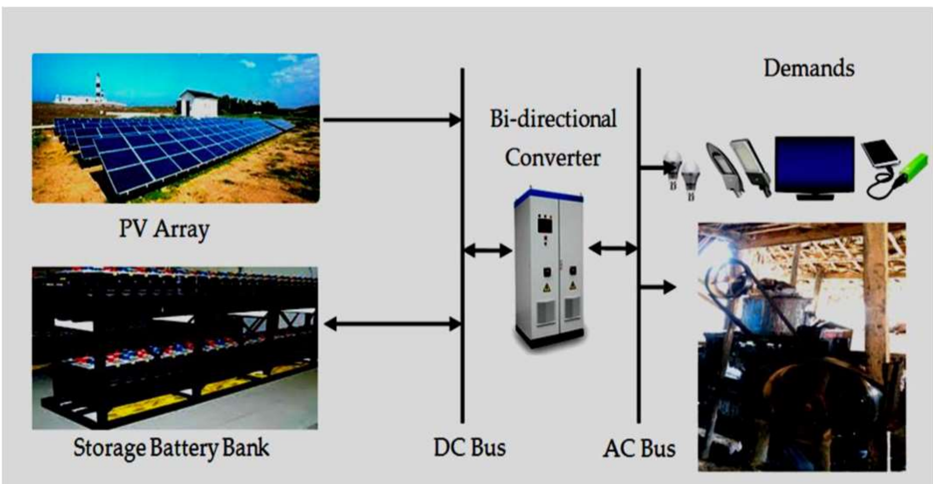
Optimal design of renewable based mini-grid systems
LCOE analysis: ***Myanmar***

【2 – Myanmar】

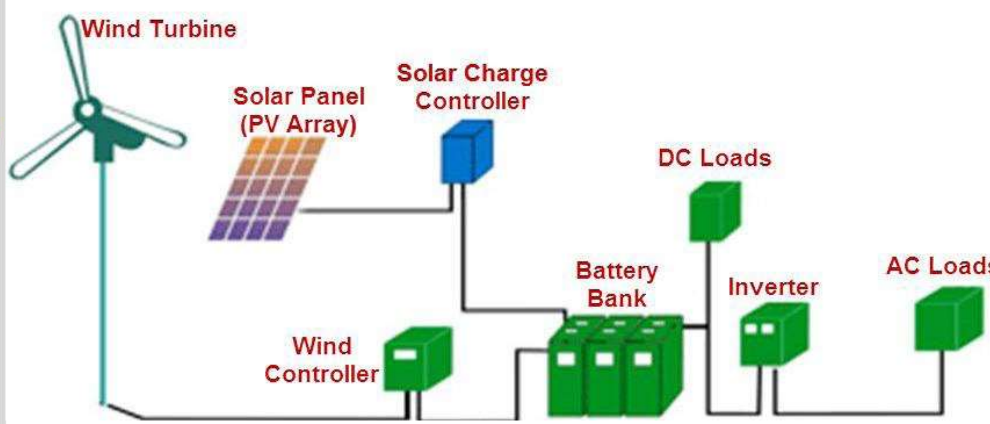
100% Renewable Mini-grid System

Village 1: **Comparison between 100% Solar PV and Diesel based mini-grid systems**
Village 2: **Comparison between 100% Renewable Hybrid (Solar PV and Wind) and Diesel based mini-grid systems**

Village 1



Village 2



Question:

1) Are 100% Renewable Hybrid Mini-grid systems economically viable compared to conventional Diesel based systems?
2) To what extent the size of Demands (Loads) affect the LCOE?

Optimal design of renewable based mini-grid systems

LCOE analysis: *Myanmar*

Key Takeaways:

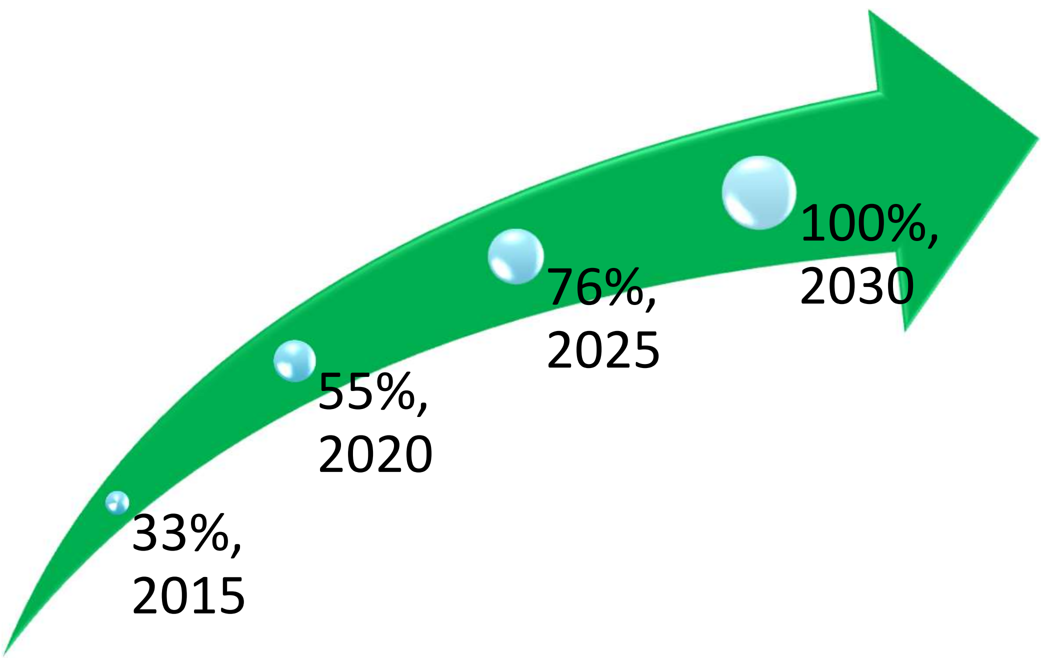
I. The LCOE of **100% Renewable based systems** **(both pure Solar PV, and hybrid Solar PV and Wind)** **is already quite compatible** **with that of conventional Diesel systems**

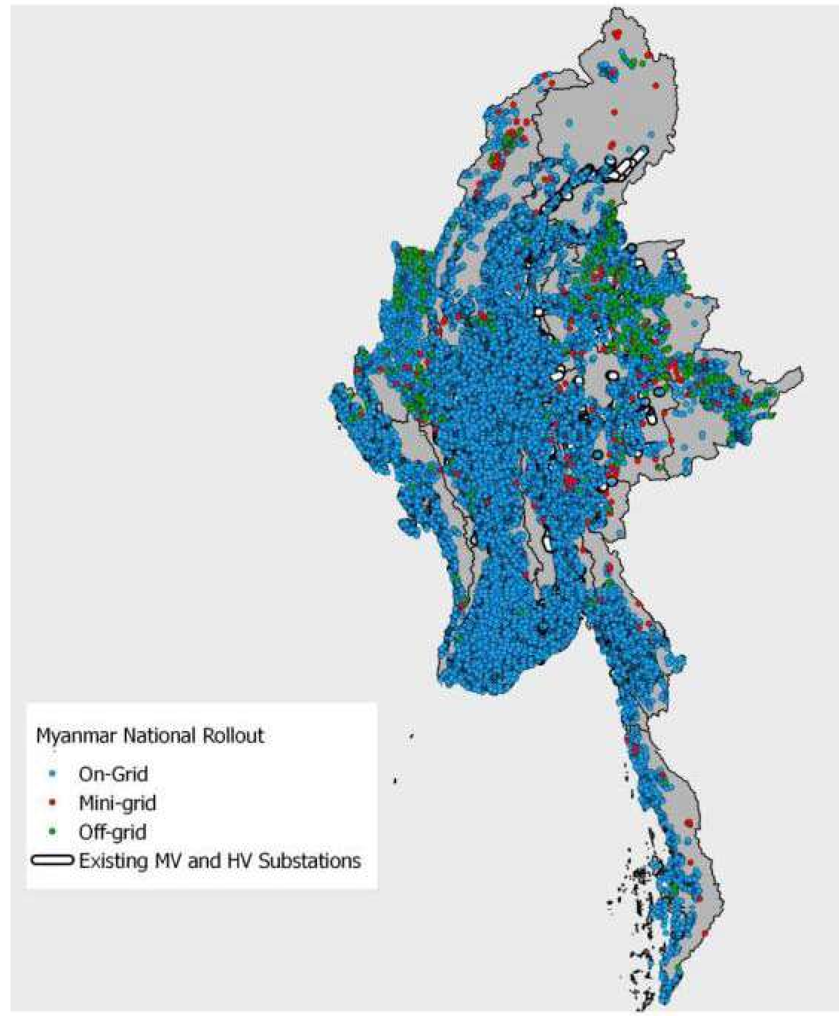
II. **The economies of scales** (driven by demands/loads) **is large for 100% renewable hybrid systems, which highlights the importance of finding and creating adequate demands/loads**

【2 - Myanmar】

Electrification rate: 40.7% (June 2018)

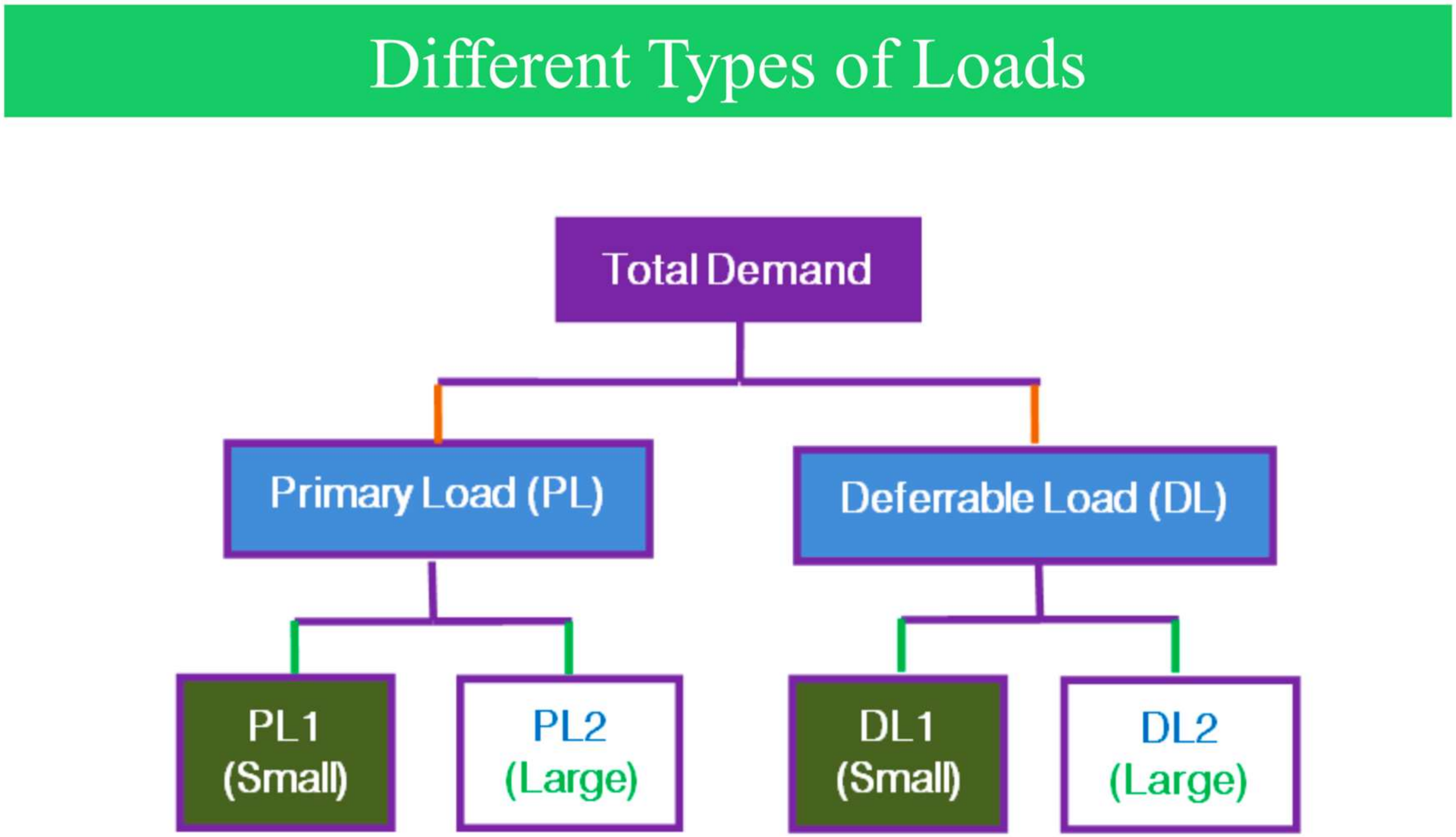
- The Government of Myanmar, with the help of the World Bank, has developed a National Electrification Plan that calls for universal electricity access by 2030





Source: DRD, 2015

【2 - Myanmar】

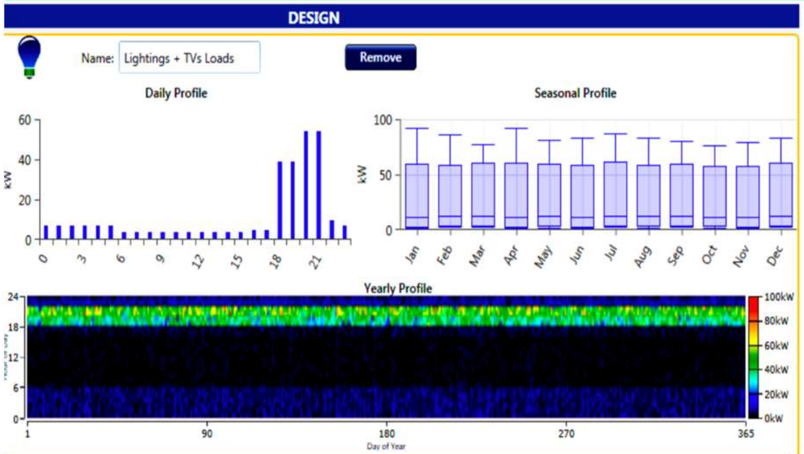

Different Types of Loads
Total Demand
Primary Load (PL)
Deferrable Load (DL)
PL1
(Small)
PL2
(Large)
DL1
(Small)
DL2
(Large)

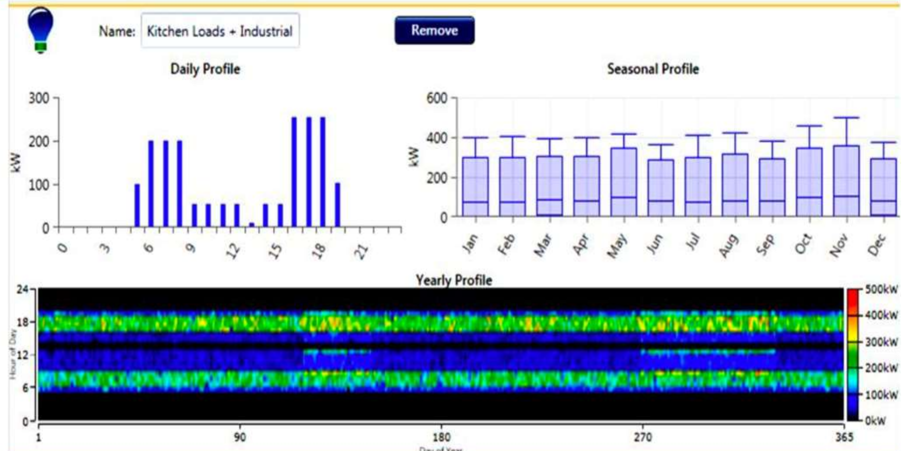
【2 - Myanmar】

Examples of DL:

【2 - Myanmar】

Village 1



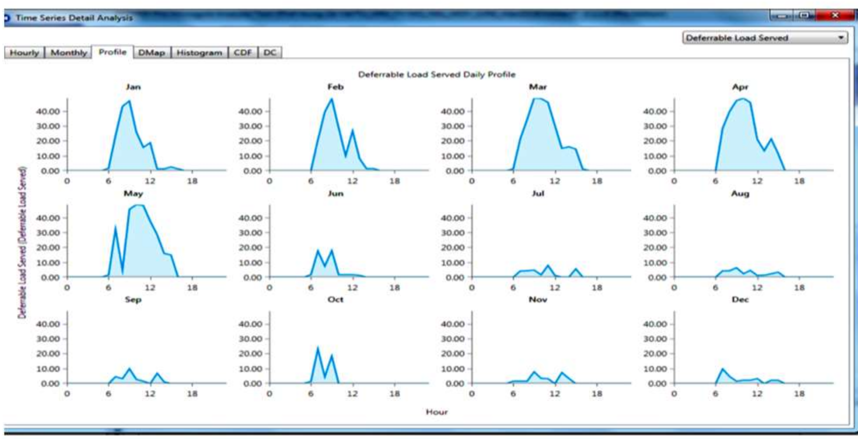


Primary Load 1

Lighting + TV Loads → 293.6 kWh per day with 92.5 kW peak

Primary Load 2

kitchen + industrial loads → 2085.72 kWh/day with 498.85 kW peak



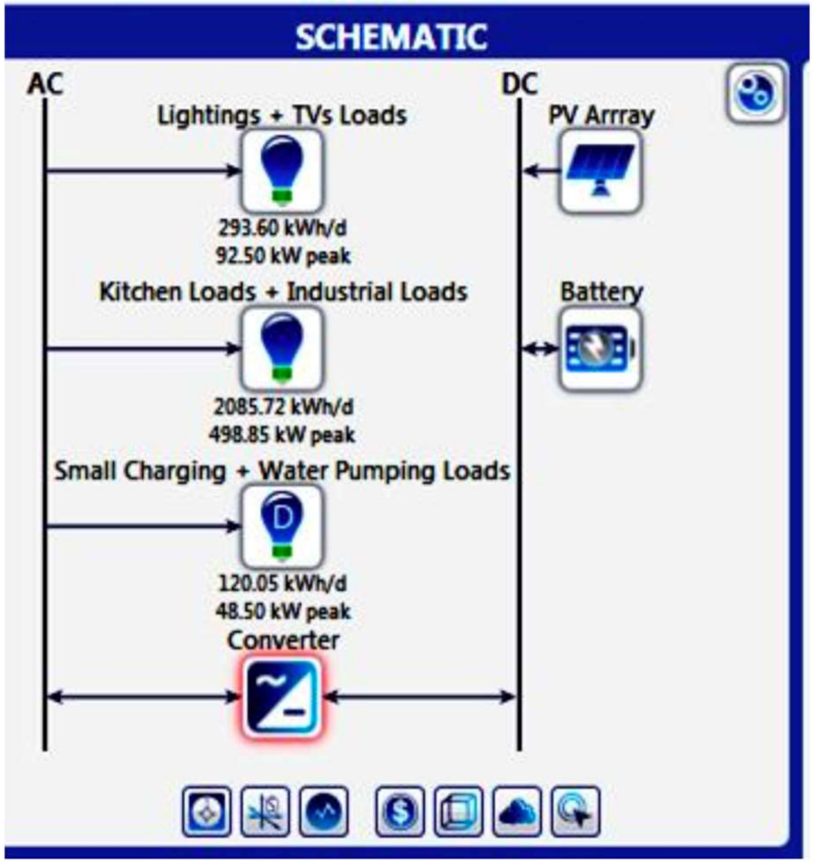
Deferrable Load

small charging & water pumping loads

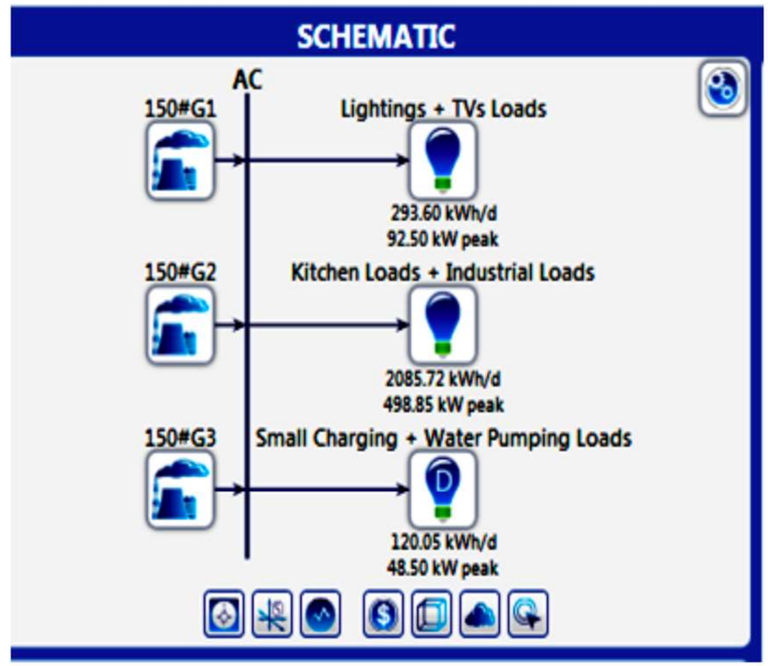
→120.05 kWh per day and 48.5 kW peak

【2 - Myanmar】

Different Models for Village 1



M1 (100% RE)



M2 (100% NRE)

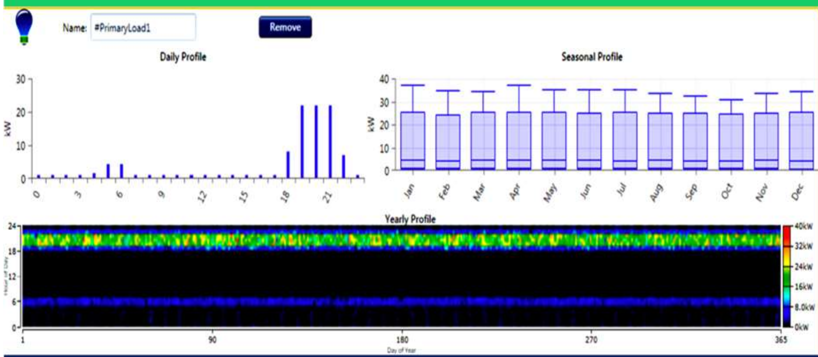
【2 - Myanmar】

Results

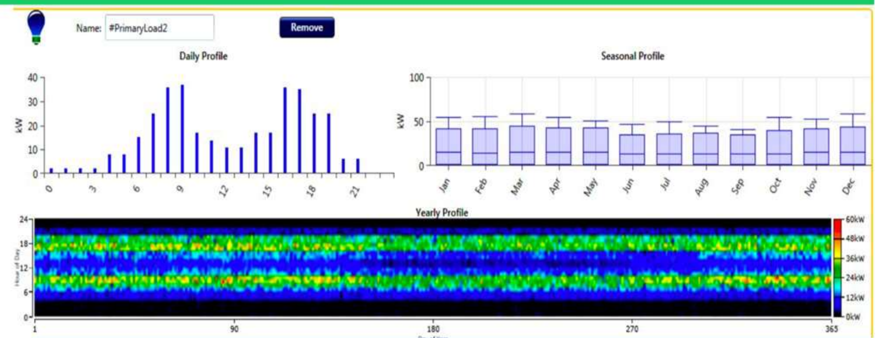
Model	Design	Annual Production (kWh/yr)	COE ($)	Net Present Cost ($)	Opera-ting Cost ($/ yr)	Initial Capital ($)	Diesel Fuel			
							Each (L/yr)	Total (L/y)	Each Cost ($/yr)	Total Cost ($/yr)
PV MG (100% RE)	PV (1032 kW)	1536344	0.289	[illegible]63 M	132826	1.57 M	-	-	-	-
	Battery (2436 kWh)	434801 (Through-put)								
	Converter (292 kW)	808240								
Diesel MG (100% NRE)	DG1 (150 kW)	729061	0.273 (at 0.62 $/L) 0.307 (at 0.72 $/L)	3.77 M (at 0.62 $/L) 4.85 M (at 0.72 $/L)	235986 (at 0.62 $/L) 264619 (at 0.72 $/L)	105000 105000	220261	288348	136562 (at 0.62 $/L) 158588 (at 0.72 $/L)	178776 (at 0.62 $/L) 207610 (at 0.72 $/L)
	DG2 (150 kW)	227535					68087		42214 (at 0.62 $/L) 49022 (at 0.72 $/L)	

【2 - Myanmar】

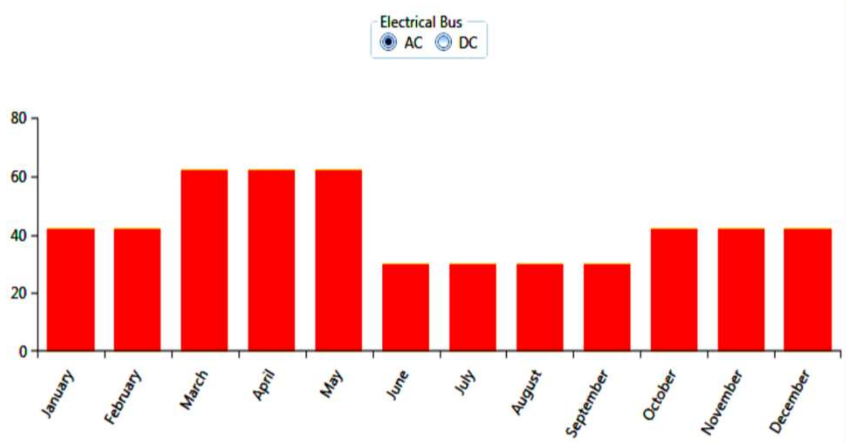
Village 2



Primary Load 1
Lighting + TV Loads → 108.6 kWh per day with 37.34 kW peak



Primary Load 2
kitchen + industrial loads → 336.24 kWh/day with 59.28 kW peak

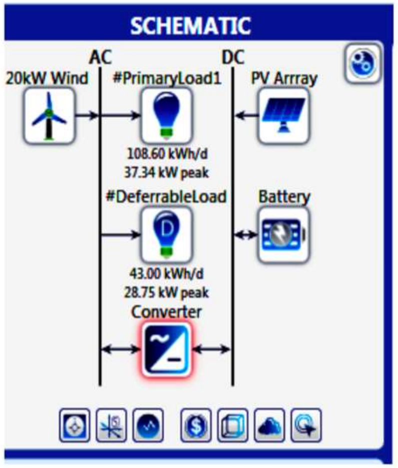


Deferrable Load
small charging & water pumping loads →43 kWh per day and 28.75 kW peak

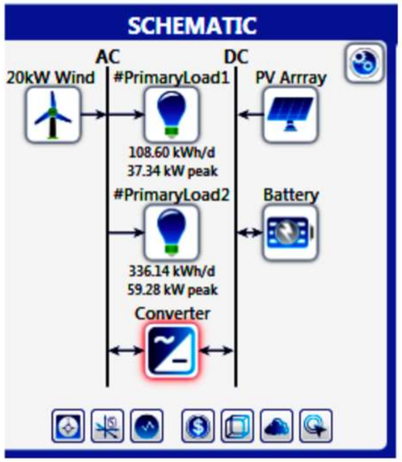
【2 – Myanmar】

Different Models for Village 2

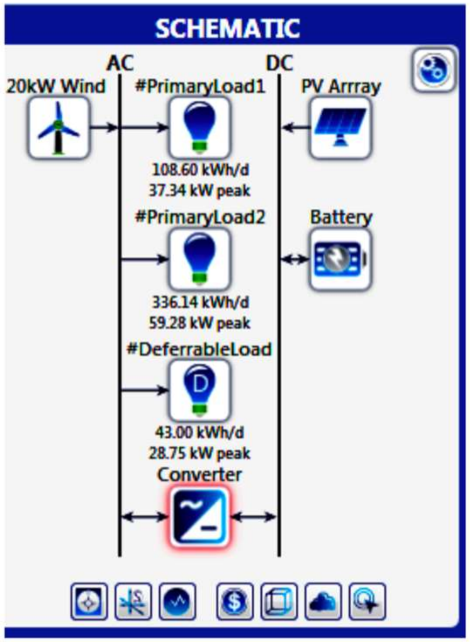
Model	Components	Demands
Model1 (M1)	PV-Wind-Battery Hybrid	PL1 and DL
Model2 (M2)	PV-Wind-Battery Hybrid	PL1 and PL2
Model3 (M3)	PV-Wind-Battery Hybrid	PL1, PL2,and DL
Model4 (M4)	Diesel Generators (50 kW & 25 kW)	PL1, PL2,and DL



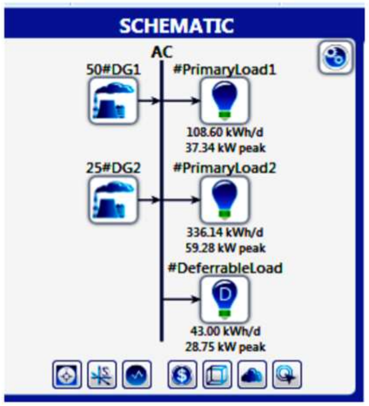
M1



M2



M3 (100% RE)



M4 (100% NRE)

【2 - Myanmar】

Results

Model	Design	Capacity	Annual Production/ Throughput (kWh/yr)	Cost of Energy ($)	Net Present Cost ($)	Operating Cost ($/ yr)	Initial Capital ($)	Diesel Fuel		
								(L/yr)	($/L)	($/yr)
M1	PV	29.4 kW	43504	0.597	479476	13990	262097	-	-	-
	Wind	60 kW	122876							
	Battery	144 kWh	19037							
	Converter	28.8 kW	-							
M2	PV	84.8 kW	125593	0.388	909898	29893	448220	-	-	-
	Wind	140 kW	286711							
	Battery	270 kWh	38361							
	Converter	55.7 kW	-							
M3	PV	87.1 kW	129044	0.352	902973	29267	448223	-	-	-
	Wind	160 kW	327670							
	Battery	243 kWh	34360							
	Converter	54.3 kW	-							
M4	DG1	50	137742	0.351	970515	53937	132429	45057	0.62	27935
									0.72	32441
	DG2	25	45975					16867	0.62	10457
									0.72	12144

【2 – Myanmar】

Yearly Plan of Off- Grid Electrification Program (2016~2021)

Sr.	Fiscal Year	SHS		Mini-Grid		Total		Remark
		Village	Household	Village	Household	Village	Household	
1	2016-2017	2708	141465	10	1503	2718	142968	Complete
2	2017-2018	1366	88019	35	6868	1401	94887	Complete
3	2018-2019	2455	132368	100	10000	2555	142368	On-Going
4	2019-2020	1500	122950	100	9095	1600	132045	Plan
5	2020-2021	1500	128550	100	7380	1600	135930	Plan
Total		9529	613352	345	34846	9874	648198	

Source: DRD, 2019

【2 - Myanmar】

63 kW Solar Mini-Grid System combined with 50 kW(Diesel Backup System)

110 kW Solar Mini-Grid System

30.72 kW Solar Mini-Grid System combined with 24 kW(Diesel Backup System)

【DRM】

DRM measures for developing Resilient Mini-grid Systems

Enhancing Disaster Preparedness and Responses	
Preparedness **Quality of hardware:**	Develop certification and standards for hardware; adopt internationally recognized standards and share best practices (**i: enforce standards for technical performance and safety; ii: mandate minimum warranties for component**)
Responses **Availability of hardware:**	Ensure an open, competitive marketplace for buying hardware (**i: reduction of customs administrative steps and public response timelines; ii: introduction of import tariff holidays and VAT exemptions**)
Disaster insurance:	Disaster insurance for RE is becoming common, but not yet available for mini-grid systems *Risk assessment of mini-grid systems is not easy – **disaster insurance for mini-grid systems could be developed initially via multi-stakeholder collaboration** (government, international organizations and agencies, insurance companies)

Optimal design of renewable based mini-grid systems

Key Takeaways:

I. Solar PV hybrid systems (with Diesel) are becoming cost-effective solutions in increasing number of locations

II. 100% Renewable based systems (both pure Solar PV, and hybrid Solar PV and Wind) are also already quite compatible with conventional Diesel systems in remote areas

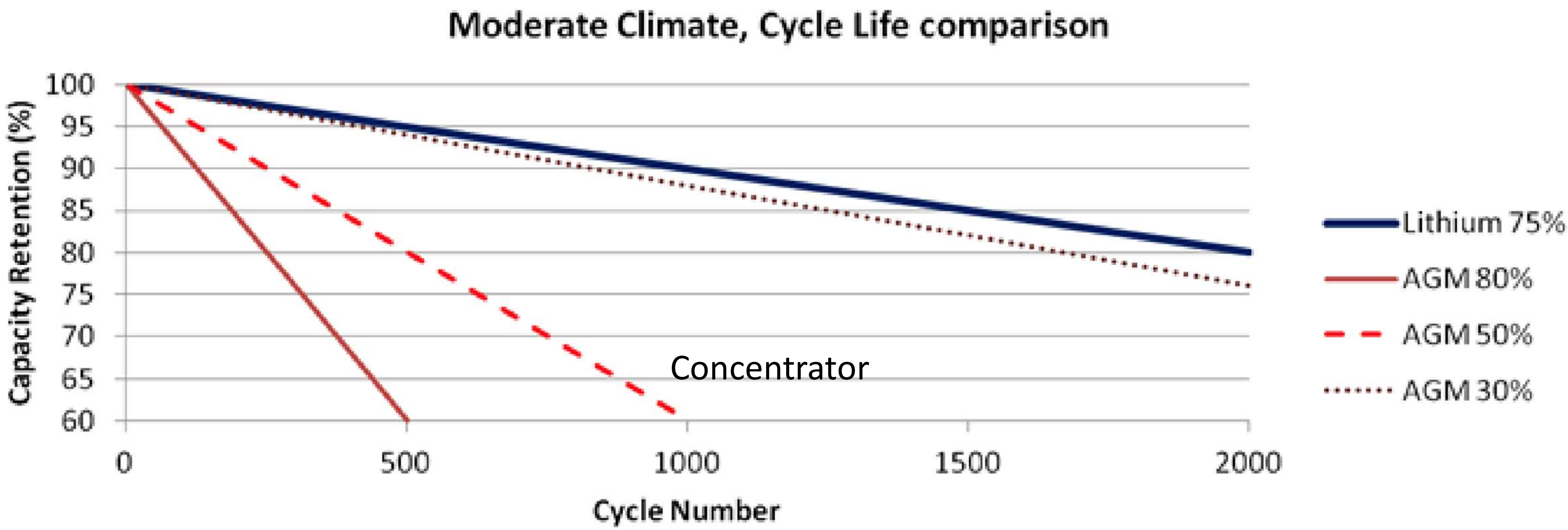
→ Economic aspects (costs) are not anymore the largest barriers, but still there are measures that could further lower the costs (e.g. access to low cost finance)

- **Regulatory and Institutional barriers need to be overcome**
- **Disaster resilience, sustainability of the systems need to be carefully considered**

Thank you

Supplemental Materials

Resilient Design: Choice of batteries

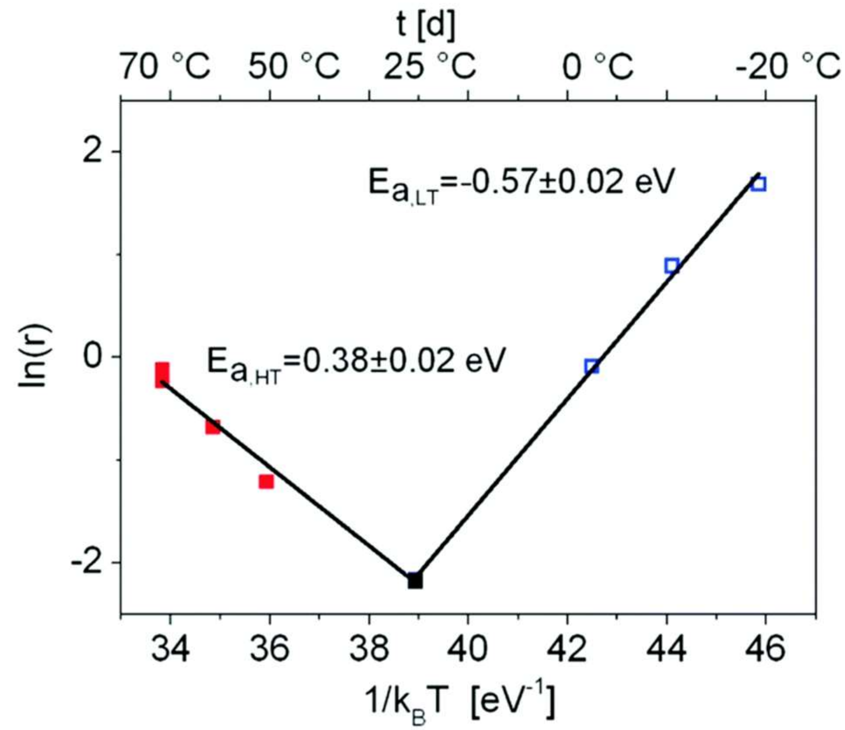


*AGM: Lead acid batteries. %: Depth of discharge

- In hot climates (average 33℃), the disparity between lithium-ion and lead acid is further exacerbated
- The cycle life for lead acid drops to 50% of its moderate climate rating while lithium-ion will remain stable until temperatures routinely exceed 49℃

Resilient Design: Choice of batteries

Temperature	40% charge	100% charge
0°C	98% (after 1 year)	94% (after 1 year)
25°C	96% (after 1 year)	80% (after 1 year)
40°C	85% (after 1 year)	65% (after 1 year)
60°C	75% (after 1 year)	60% (after 3 months)

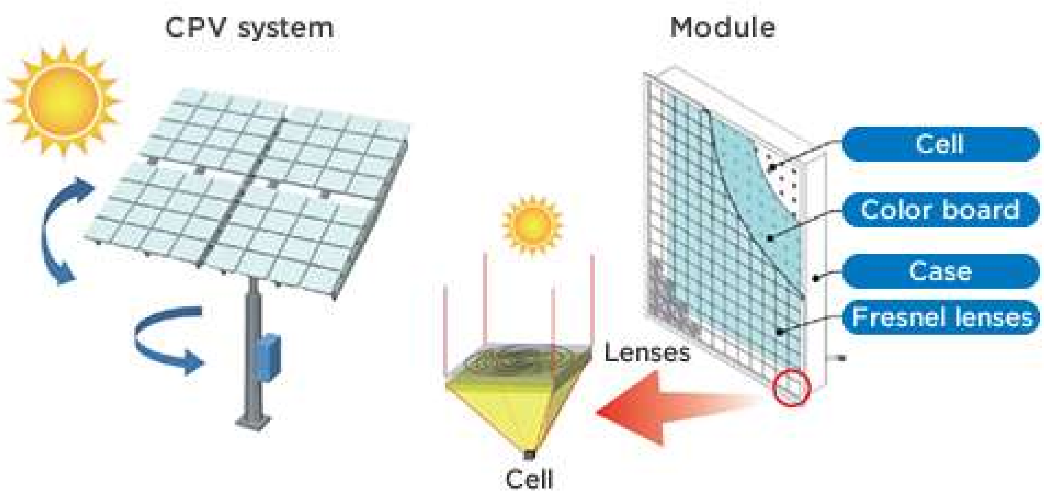


- Exposing the battery to high temperature and dwelling in a full state-of-charge for an extended time can be more stressful than cycling

Between 25 ℃ and 70 ℃, the ageing rate increases with increasing temperature and the trend is reversed between 25 ℃ and −20 ℃. At high temperature transition metal dissolution is enhanced while at low temperature, the predominant ageing mechanism is lithium plating and subsequent reaction with the electrolyte, leading to loss of cyclable lithium.

Resilient Design: Solar PV

1) Concentrator Solar PV (CPV)



Sumitomo Electric Industries, Ltd. is designed for high solar radiation, and high-temperature areas (Morocco, Australia etc.). The impact of high temperature on the efficiency is negligible compared to silicon solar cells.

2) Floating Solar PV (FPV)

Source: © Ciel & Terre International.

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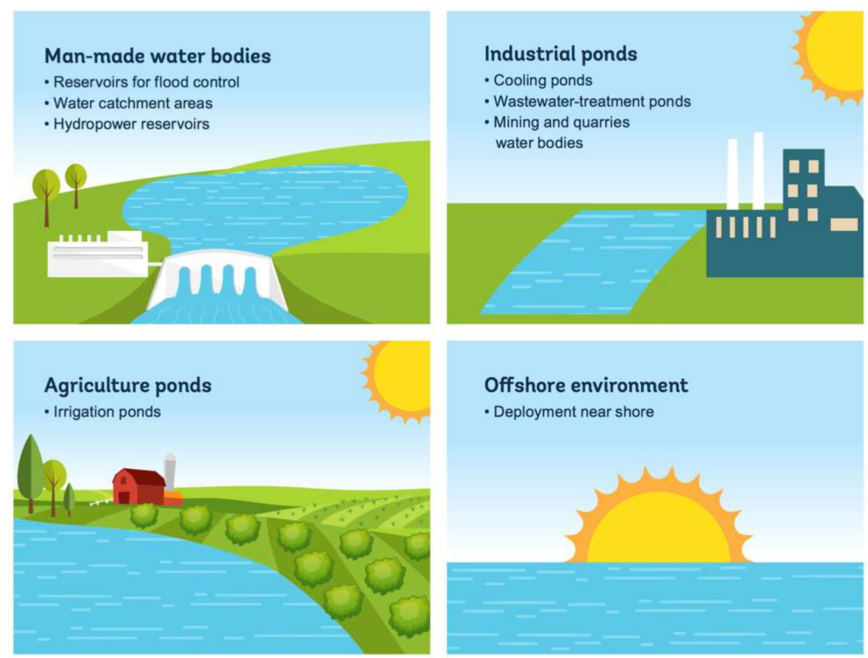

Resilient Design: Data for Flow Duration

1) Large river – 50kW mini-hydro

Site Specific Flow Duration Curve is not too important for the design. Design could be made based on available data (nearby dams, simulation data).

2) Small streams

Site Specific Flow Duration Curve is very important for the design. Design should be made based on high-accuracy data.