The evaluation of a prototype 25 kW/50 kWh Zn-Br_2 redox flow battery for integration with a 225 kW wind turbine

Leonard Berlouis[a], Declan Bryans[a], Brian McMillan[a], Jawwad Zafar[a], Paul Tuohy[a], Tae Hyuk Kang, Dae Sik Kim[b], Dong Joo Kim[b], Michael Shaw[c], Patrick Atkinson[c] and Andrew Peacock[d].

[a] University of Strathclyde, Glasgow, [b] Lotte Chemical Research Institute, Daejeon, South Korea, [c] Findhorn Foundation College, Forres, nr. Inverness, [d] Heriot Watt University, Edinburgh.

Research & Development project

LOTTE CHEMICAL

smarter grid solutions

University of Strathclyde Glasgow

Greener Scotland
Scottish Government

HERIOT WATT UNIVERSITY

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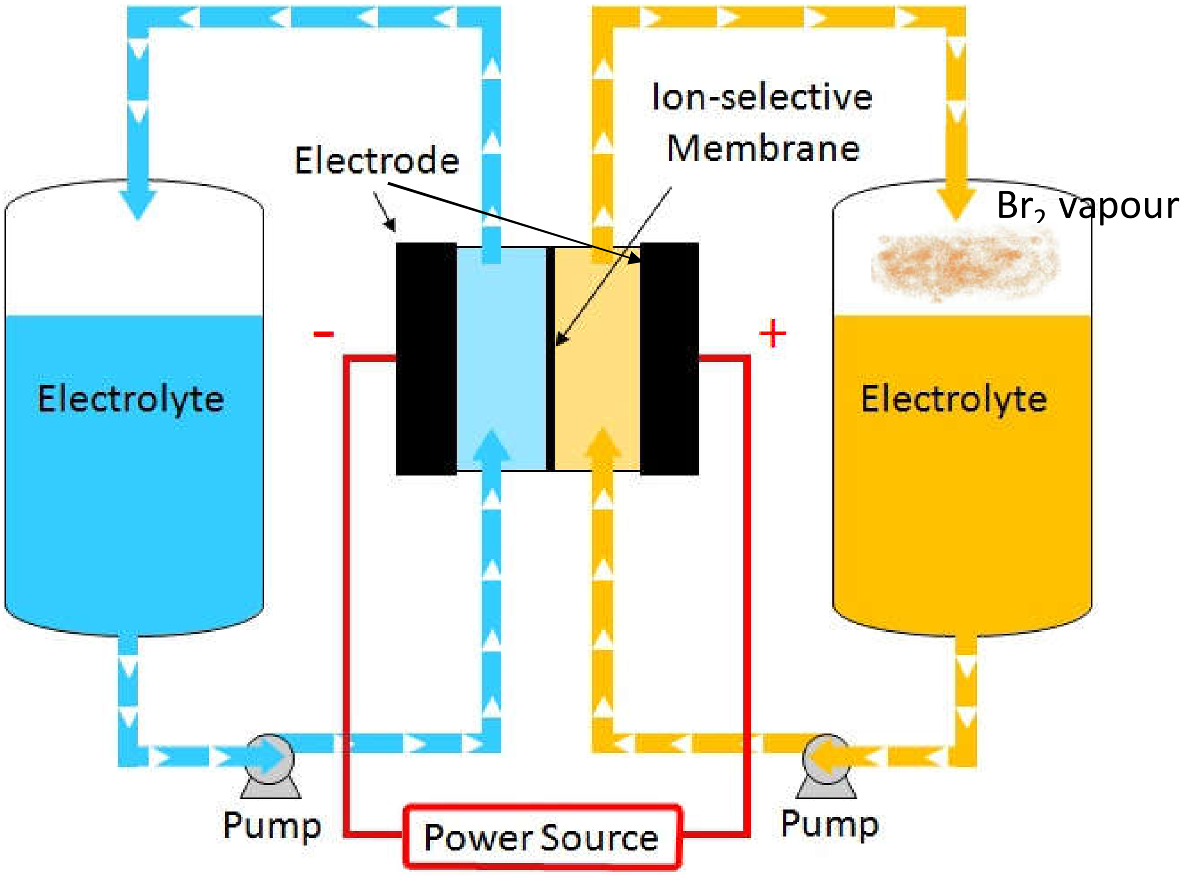
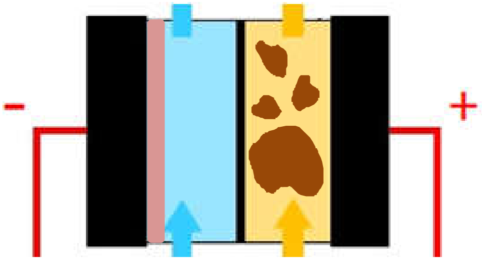
TÜV SÜD nel
technology for life

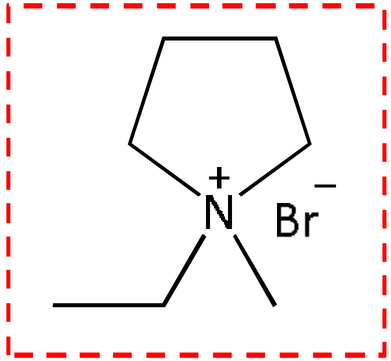
Zinc-Bromine RFB



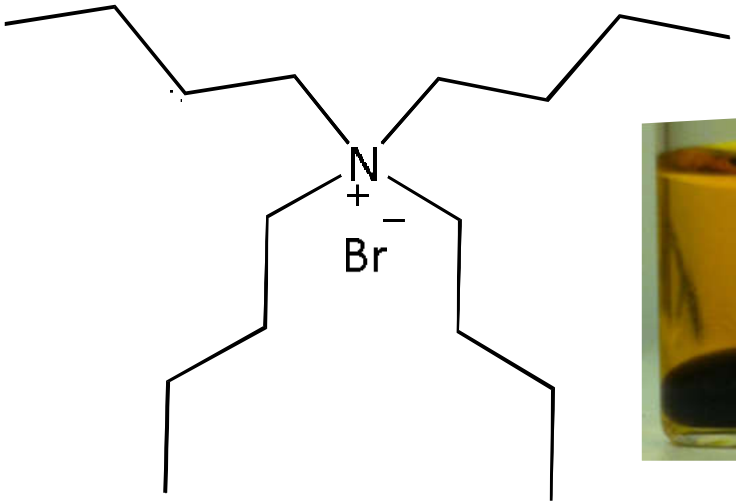
$2Br^- \rightarrow Br_{2\,(l)} + 2e^-$ $\quad E° = 1.087$ V *vs* SHE

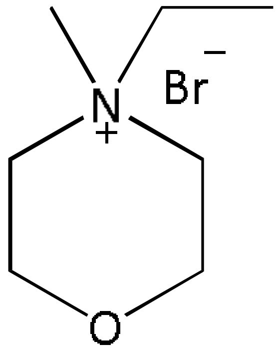
$Zn^{2+} + 2e^- \rightarrow Zn_{(S)}$ $\quad E° = -0.76$ V *vs* SHE





N-Ethyl-*N*-methylpyrrolidinium bromide
(MEP)





Tetrabutylammonium bromide
(TBA)

N-Ethyl-*N*-methylmorpholinium bromide
(MEM)

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- The PNDC was founded through support from the University of Strathclyde, The Scottish Funding Council, Scottish Enterprise, Scottish Power and Scottish and Southern Energy

- Real 11 kV and LV distribution networks,
  - flexible with the ability to vary voltage, frequency and perform disturbance testing in a controlled environment.

- The capability to research, test and demonstrate hardware, software and integrated systems solutions in a safe, controlled environment.

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Fan heating system to maintain temperature inside GRP

Ventilation system providing 30 changes per hour of the GRP air volume.

The Bromine gas detector display inside the PNDC building

LCFB50 v1.0-2015 zinc-bromine flow battery module

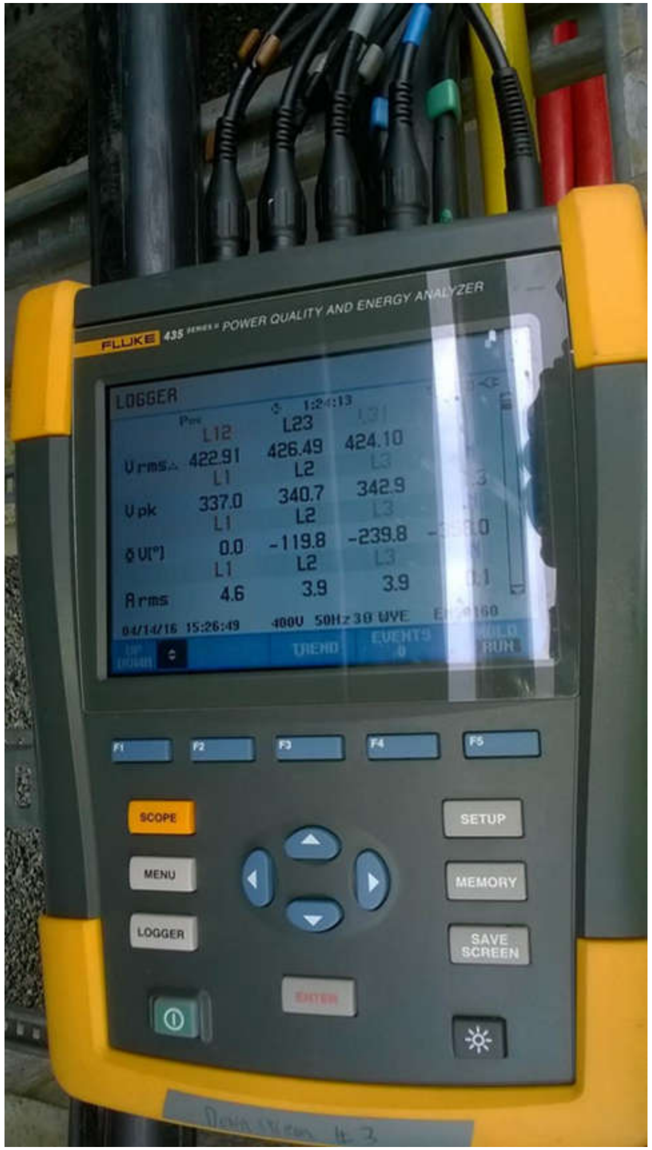
Initial tests

- The system was repeatedly charged to 30 % SoC and afterwards discharged completely, in the constant current (CC) mode selected for both charging and discharging.

- The energy flow was recorded for each charge and discharge part of the cycle using the Fluke 435-II power quality analyser
  - installed at the connection point of the Lotte battery system to the electricity network at the PNDC.

Three-phase 63 A power flow connection from the battery to the electricity network.

Fluke i1000s AC current clamps are used with the Fluke 435-II power quality analyser for measurements

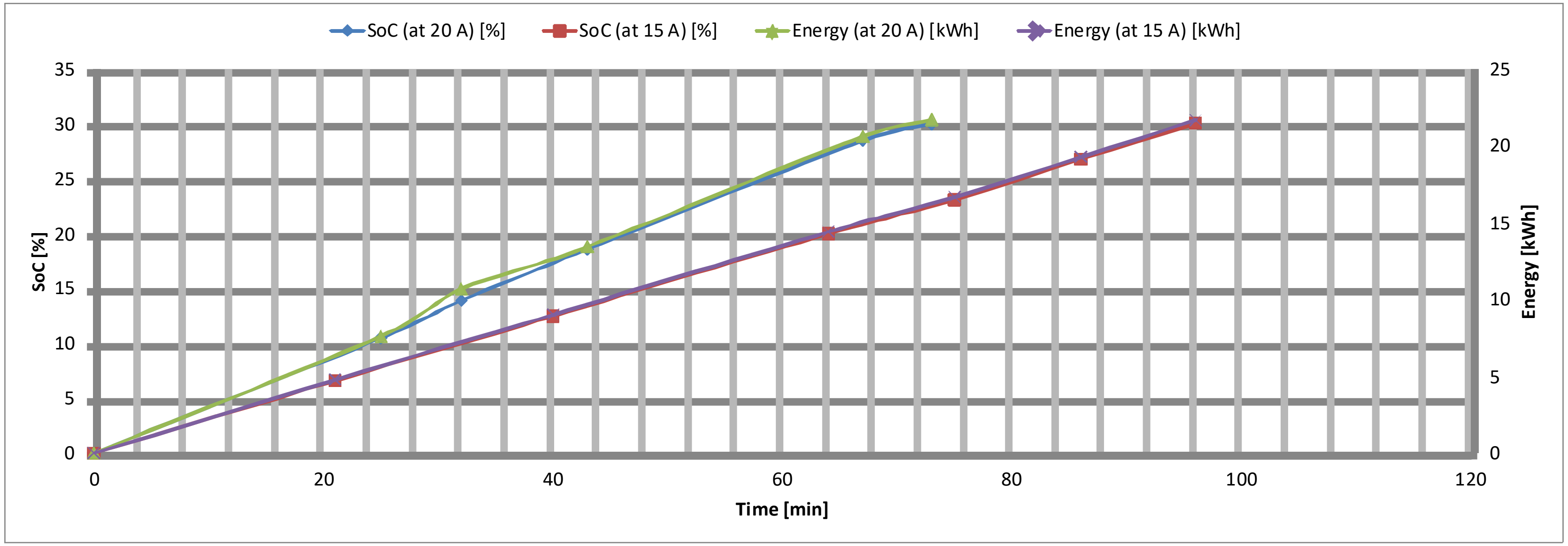


Fluke 435-II power quality analyser used to measure electrical parameters

Voltage observed at the output of DC/DC converters for different charging currents

Current /A	Voltage /V
2	210
5	214
10	220
15	224
20	234

Time taken to achieve SoC 30 % in constant current mode with 15 A and 20 A.

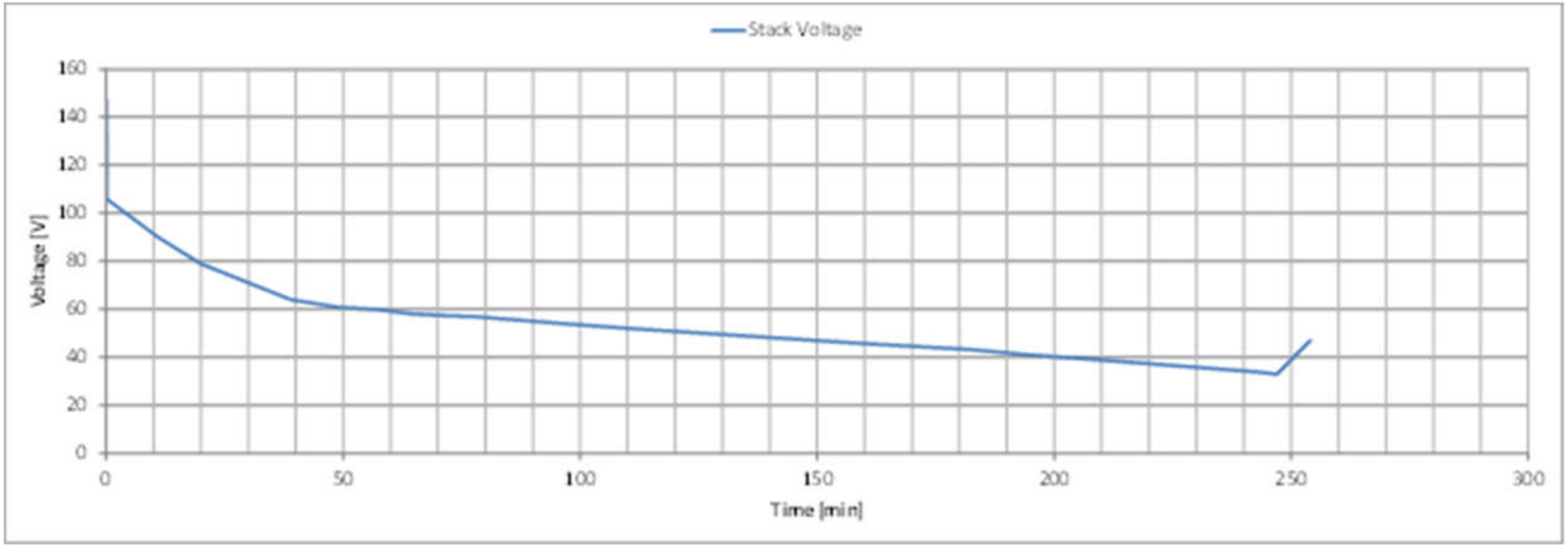


Voltage observed at the output of DC/DC converters for different discharge currents

Current /A	Voltage /V
0	210
-5	206
-10	202
-15	196

Stripping

- Stripping mode is used to discharge remaining energy from the stacks while the DC/DC converters are off.
- It is carried out to recondition the stacks every few cycles, through removing deposited zinc from the electrode, by connecting a resistor across the terminals of the stack.
- The stack voltage decays during the stripping mode and this may take several hours.



AC efficiency values for test cycles (30% SoC).

Cycle No.	SoC %	Charge Current /A	Time /min	Energy [kWh]	Discharge Current /A	Time /min	Energy /kWh	Efficiency %
1	31.2	20	75	24.1	15	110	13.5	55.9
2	31.1	20	78	23.5	15	101	15.2	64.7
3	30.1	15	94	22.7	15	111	14.3	63.1
4	30.2	15	92	22.5	15	95	14.2	62.9
5	30.1	15	90	23.1	15	93	13.9	60.4
6	30.2	15	98	23.1	15	115	14.1	60.9
7	30.3	15	95	23.2	15	98	13.6	58.7
8	30.1	15	96	23.1	15	114	13.8	60
9	30.2	15	96	23.2	15	98	13.6	58.7
10	30.2	15	96	23.1	15	108	13.7	59.4

AC efficiency values for test cycles (30% SoC).

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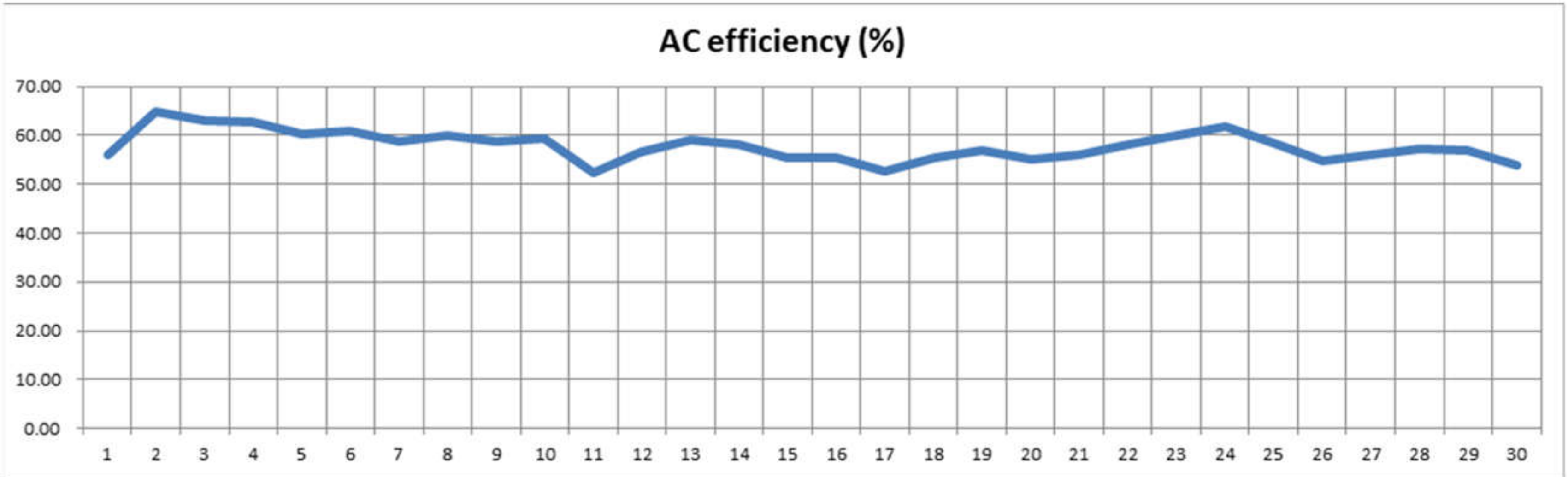
2	31.1	20	78	23.5	15	101	15.2	64.7
3	30.1	15	94	22.7	15	111	14.3	63.1
4	30.2	15	92	22.5	15	95	14.2	62.9
5	30.1	15	90	23.1	15	93	13.9	60.4
6	30.2	15	98	23.1	15	115	14.1	60.9
7	30.3	15	95	23.2	15	98	13.6	58.7
8	30.1	15	96	23.1	15	114	13.8	60
9	30.2	15	96	23.2	15	98	13.6	58.7
10	30.2	15	96	23.1	15	108	13.7	59.4

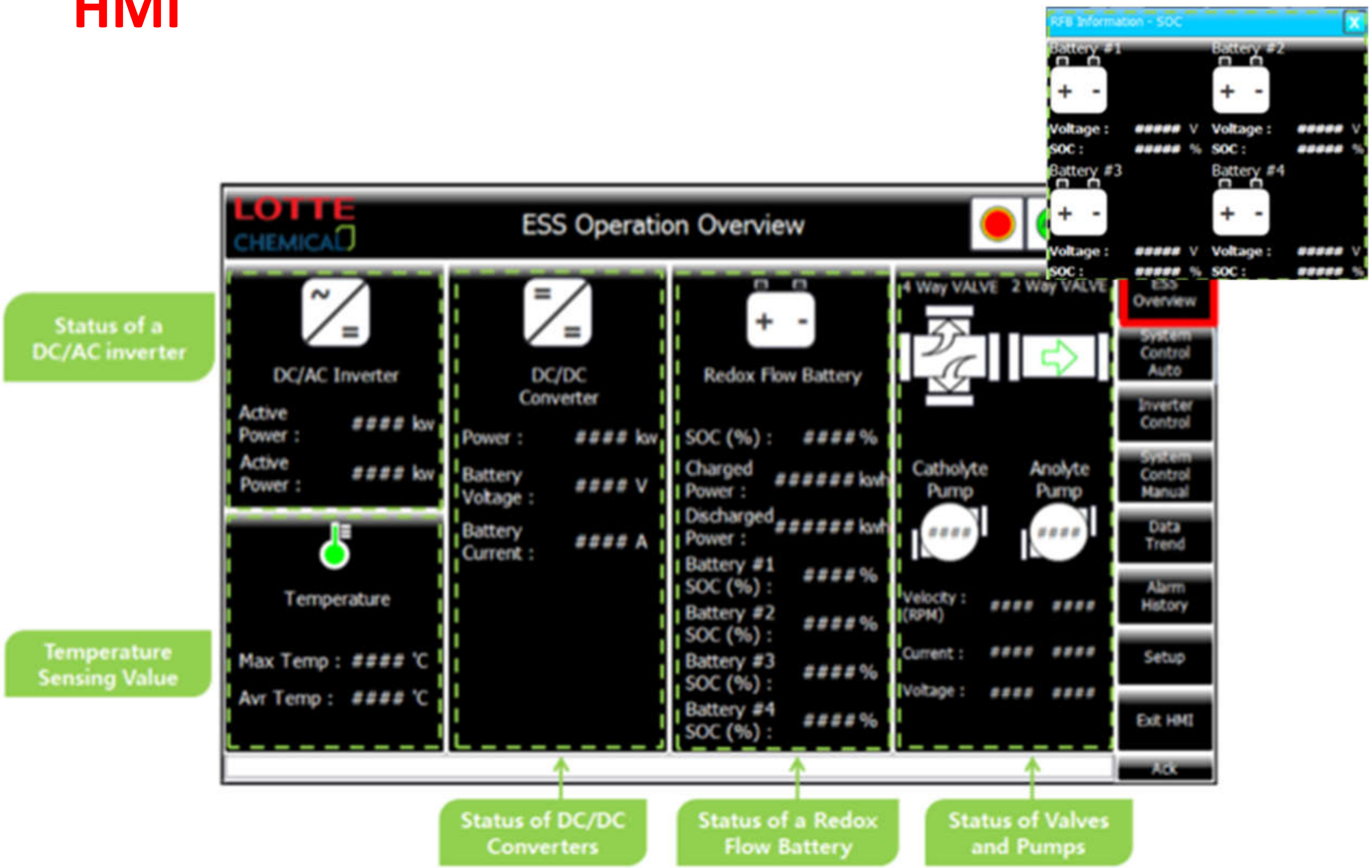
Energy efficiency overview across the test cycles (SoC 30%).



Tests at 80% SoC

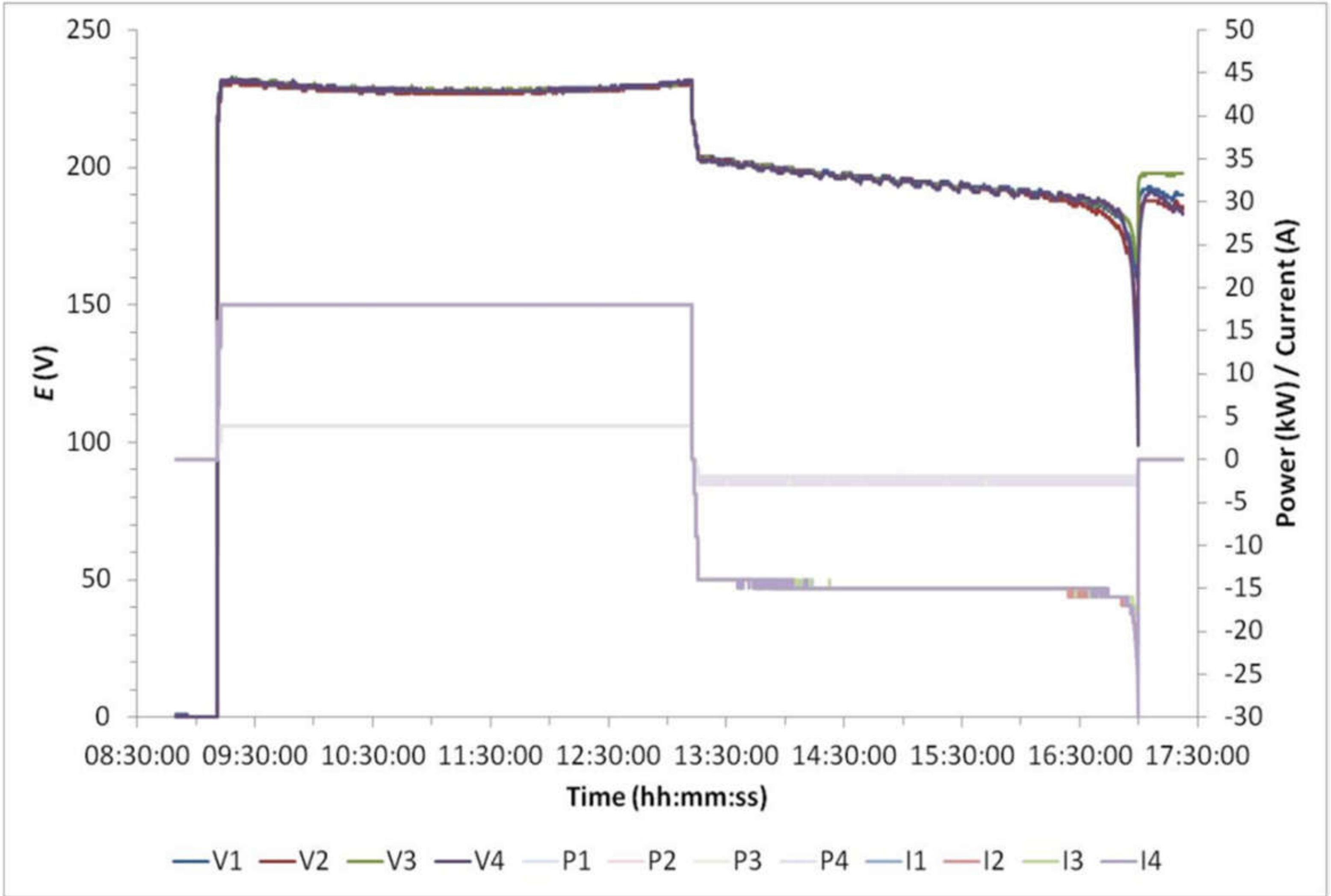
Constant power charge and discharge

HMI

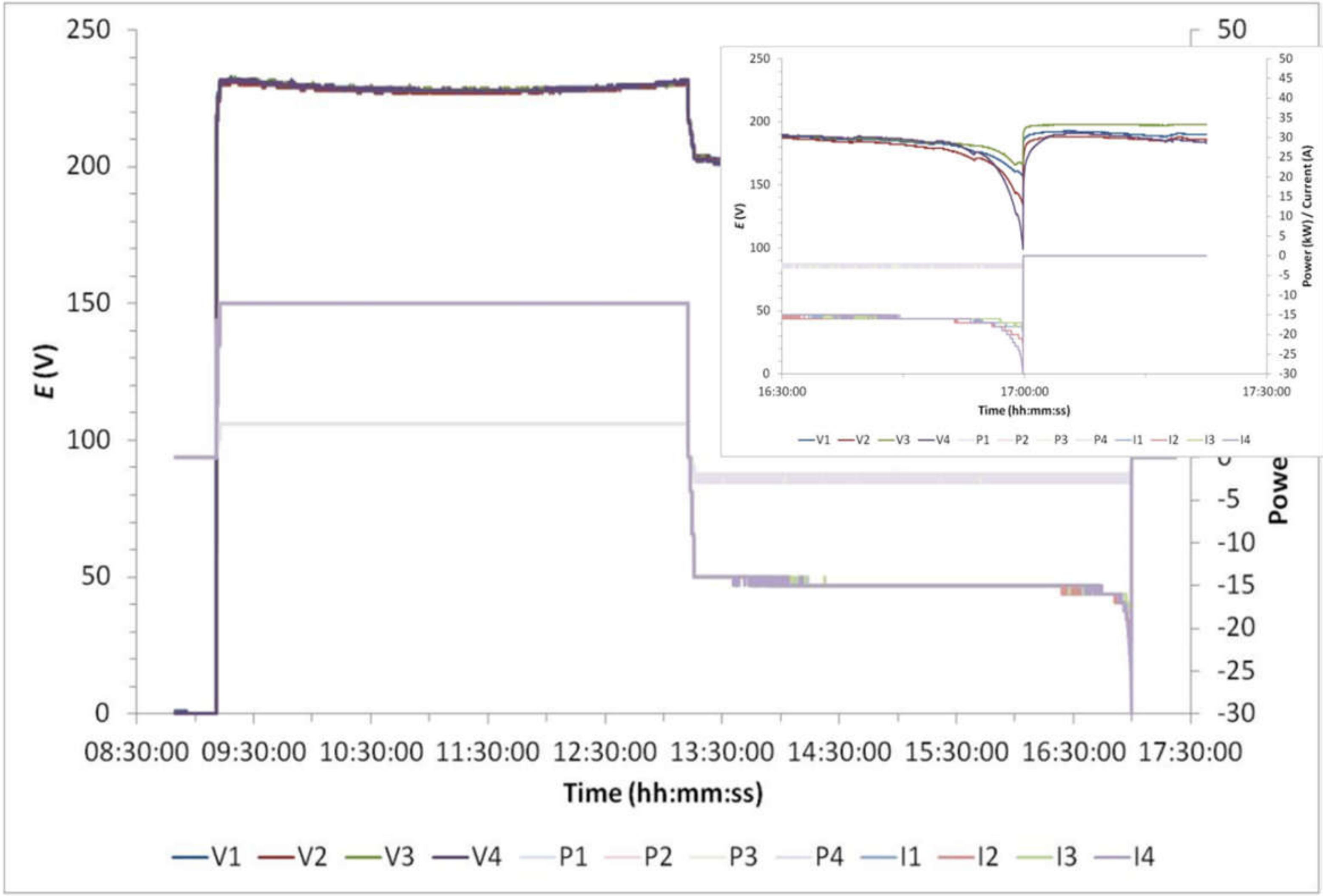


Status of a DC/AC inverter
Temperature Sensing Value
Status of DC/DC Converters
Status of a Redox Flow Battery
Status of Valves and Pumps
LOTTE CHEMICAL
ESS Operation Overview
RFB Information - SOC
Battery #1
Battery #2
Battery #3
Battery #4
Voltage :
SOC :
DC/AC Inverter
Active Power : #### kw
Active Power : #### kw
Temperature
Max Temp : #### ℃
Avr Temp : #### ℃
DC/DC Converter
Power : #### kw
Battery Voltage : #### V
Battery Current : #### A
Redox Flow Battery
SOC (%) : ####%
Charged Power : ###### kwh
Discharged Power : ###### kwh
Battery #1 SOC (%) : ####%
Battery #2 SOC (%) : ####%
Battery #3 SOC (%) : ####%
Battery #4 SOC (%) : ####%
4 Way VALVE
2 Way VALVE
Catholyte Pump
Anolyte Pump
Velocity : (RPM)
Current :
Voltage :
ESS Overview
System Control Auto
Inverter Control
System Control Manual
Data Trend
Alarm History
Setup
Exit HMI
Ack

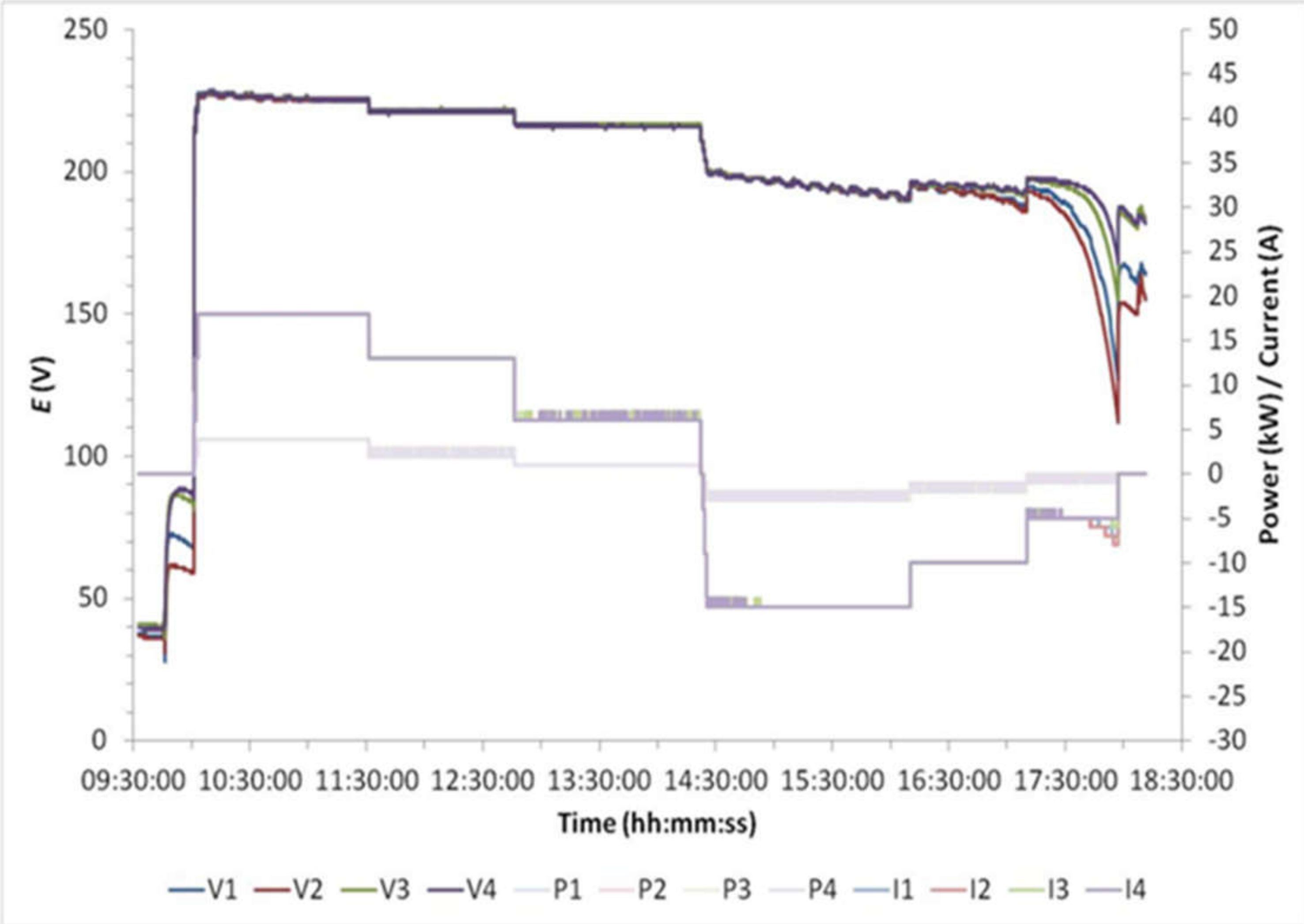
17 kW charge/ 12 kW discharge



17 kW charge/ 12 kW discharge



Staggered charge/ discharge cycle



Summary Data Table

	Charge Cycle			Discharge Cycle			Efficiency	
Run	Power /kW	Time /min	Charge /kWh	Power /kW	Time /min	Discharge /kWh	DC/DC %	AC/AC %
1	12	120	23.9	−8	120	15.7	66	55
2	17	200	59.6	−12	220	40.4	68	58
3	17/12/6	90/75/100	49.7	−12/−8/−4	105/60/50	32.2	65	54
4	17	240	68.1	−12	240	44.9	66	56
5	17	180	51.1	−8	255	33.7	66	55
6	17	180	51.1	−4	420	28.3	55	43
7	17	60	17.2	−14	60	8.8	51	39
8	17	180	51.1	−12	180	34.4	67	57
9	12	180	35.9	−8	190	23.8	66	56
10	8	180	23.8	−4	240	14.6	61	48

Summary Data Table

	Charge Cycle			Discharge Cycle			Efficiency	
Run	Power /kW	Time /min	Charge /kWh	Power /kW	Time /min	Discharge /kWh	DC/DC %	AC/AC %
1	12	120	**23.9**	−8	120	15.7	66	**55**
2	17	200	**59.6**	−12	220	40.4	68	**58**
3	17/12/6	90/75/100	**49.7**	−12/−8/−4	105/60/50	32.2	65	**54**
4	17	240	**68.1**	−12	240	44.9	66	**56**
5	17	180	**51.1**	−8	255	33.7	66	**55**
6	17	180	**51.1**	−4	420	28.3	55	**43**
7	17	60	**17.2**	−14	60	8.8	51	**39**
8	17	180	**51.1**	−12	180	34.4	67	**57**
9	12	180	**35.9**	−8	190	23.8	66	**56**
10	8	180	**23.8**	−4	240	14.6	61	**48**

Summary Data Table

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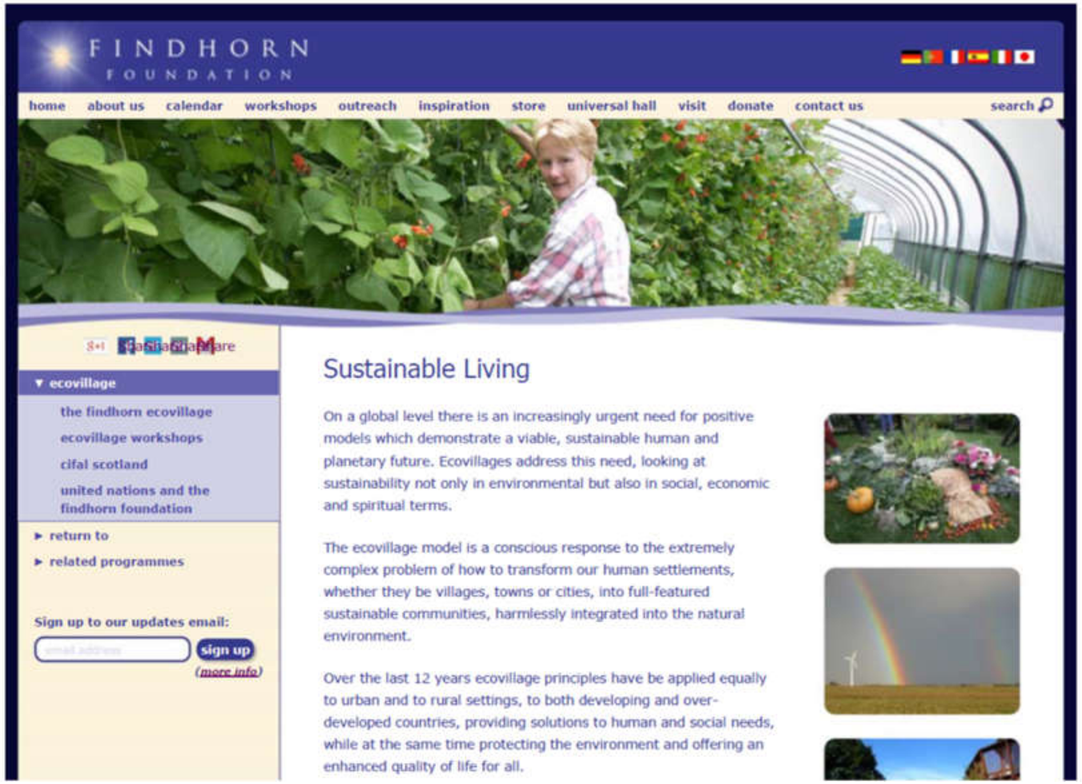
3	17/12/6	90/75/100	**49.7**	−12/−8/−4	105/60/50	32.2	65	**54**
4	17	240	**68.1**	−12	240	44.9	66	**56**
5	17	180	**51.1**	−8	255	33.7	66	**55**
6	17	180	**51.1**	−4	420	28.3	55	**43**
7	17	60	**17.2**	−14	60	8.8	51	**39**
8	17	180	**51.1**	−12	180	34.4	67	**57**
9	12	180	**35.9**	−8	190	23.8	66	**56**
10	8	180	**23.8**	−4	240	14.6	61	**48**

Update

- Changes have since been made by Lotte Chemical to the flow battery module (LCFB65 V1.1-2018) and power conversion system:
  - an increase in overall energy efficiency
  - an increase in FB module capacity to 62.5 kWh

Findhorn Foundation Community

Findhorn

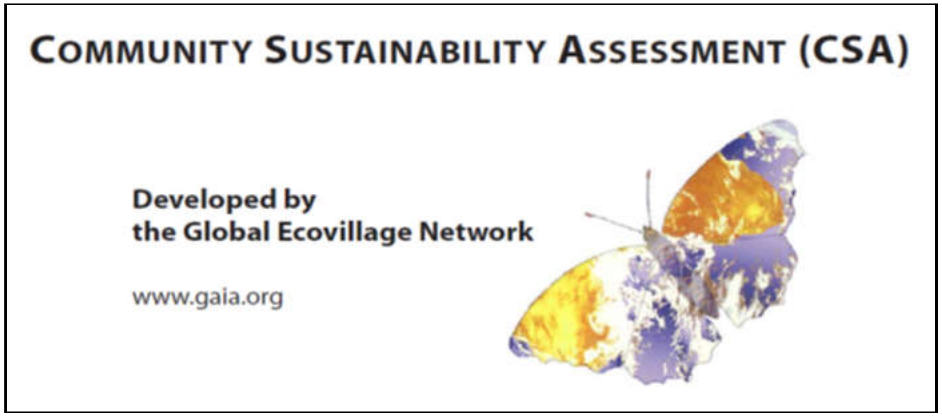


(tuohy@esru.strath.ac.uk)

Ecovillages and optimisation of Renewable energy supply and demand.

What is an Ecovillage – criteria?

- Bioregional – I Planet
- Global Ecovillages Network (GEN)



- Health and happiness
- Equity and local economy
- Culture and community
- Land use and wildlife
- Sustainable water
- Local and sustainable food
- Sustainable materials
- Sustainable transport
- Zero waste
- Zero carbon

(tuohy@esru.strath.ac.uk)

http://origin-concept.eu/

Findhorn Foundation College

ORIGIN: Findhorn, Damanhur, Tamera

Orchestration of Renewable Integrated Generation in Neighbourhoods

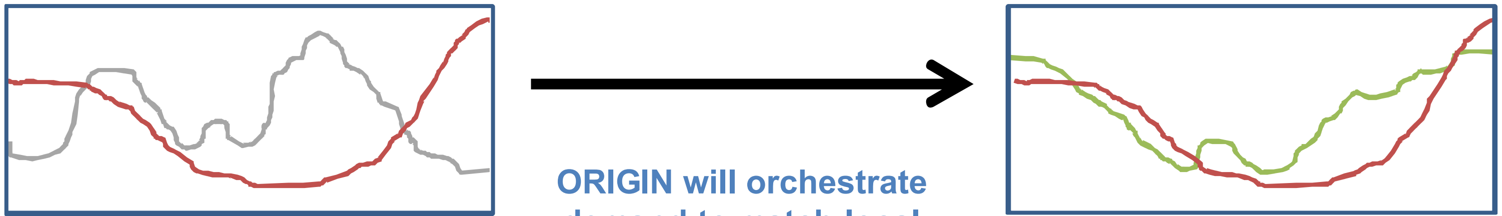
(tuohy@esru.strath.ac.uk)

http://origin-concept.eu/

ORIGIN: Orchestration of Renewable Integrated Generation in Neighbourhoods

Now

ORIGIN goal: + 20% Local Renewable Use



ORIGIN will orchestrate demand to match local supplies through:

1. People controlled loads to be influenced by information and tariffs (PCLs).
2. Electrical controllable loads: Pumps, EV charging, Batteries, Appliances (ECLs).
3. Thermostatic controllable loads: Space and Water heating or cooling (TCLs).

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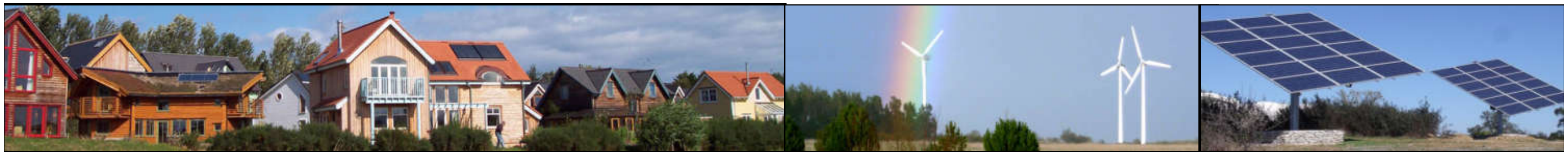
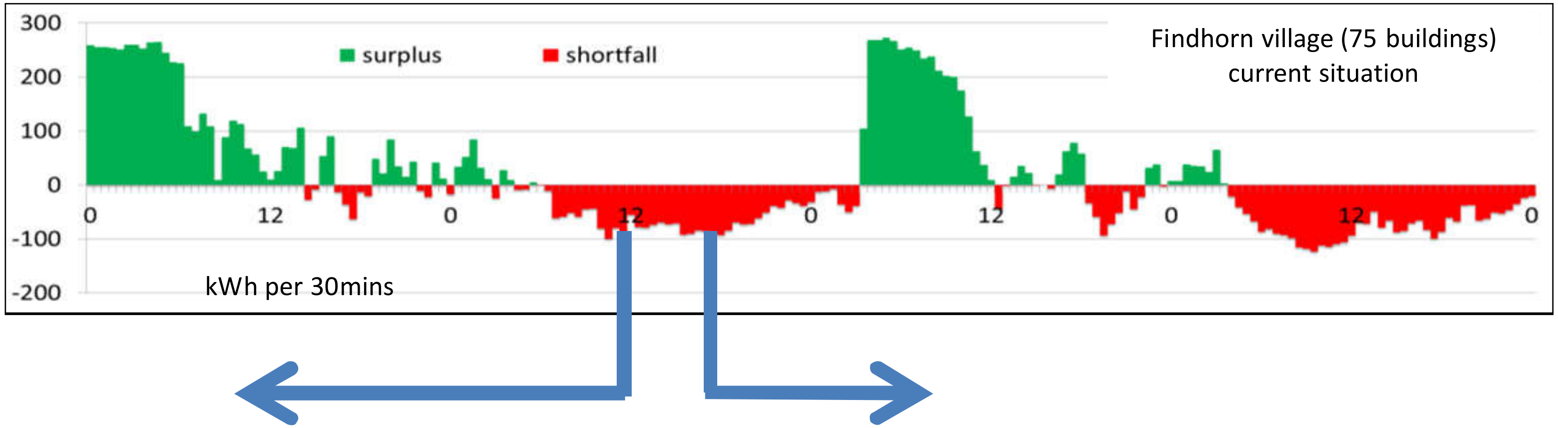
ORIGIN: Orchestration of Renewable Integrated Generation in Findhorn



We want to avoid imports from the grid (red) by using renewable when available (green)



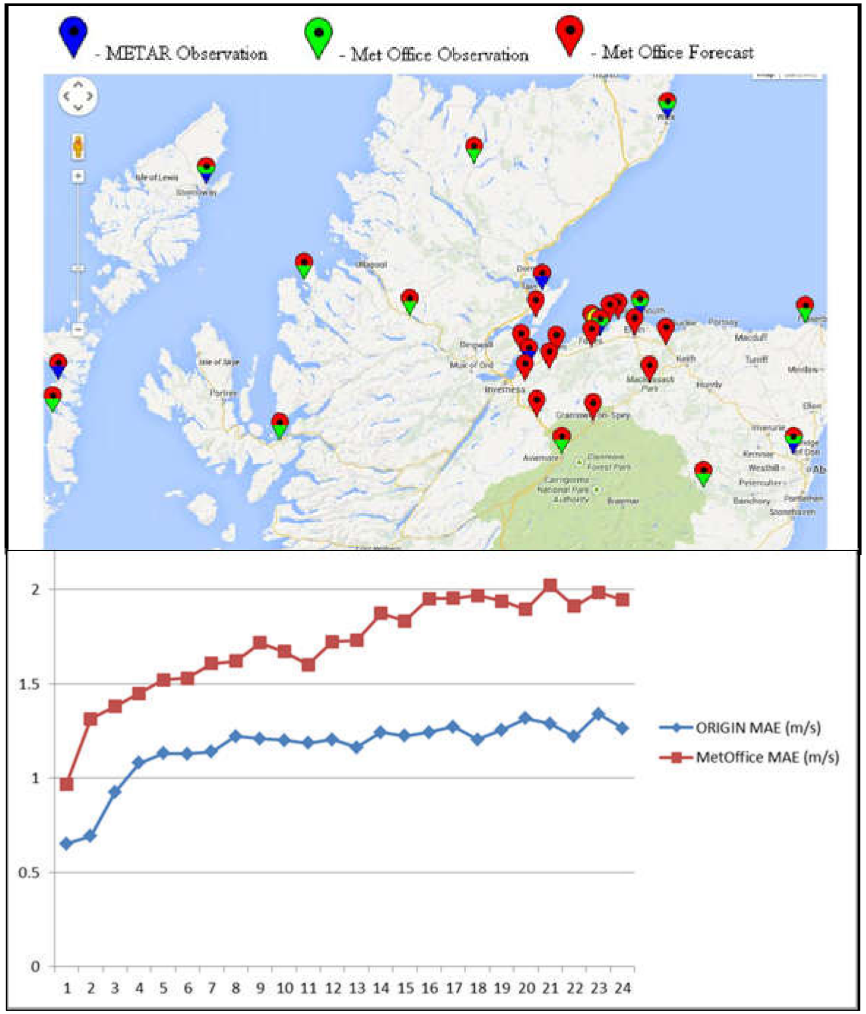
change demands by providing information and remote controls based on weather and demand forecasting smart learning algorithms

(tuohy@esru.strath.ac.uk)

http://origin-concept.eu/

ORIGIN Advanced Weather Prediction

- Takes forecast and observation data for many surrounding sites.
- Predicts next 48 hours local weather using neural networks and regression models.
- Improves on Met Office forecasts.
- Graph is wind speed at Findhorn
  - Vertical axis is m/s error.
  - Horizontal axis is 'hours ahead'.
- Similar methods used for generation and demand prediction plus gap analysis.



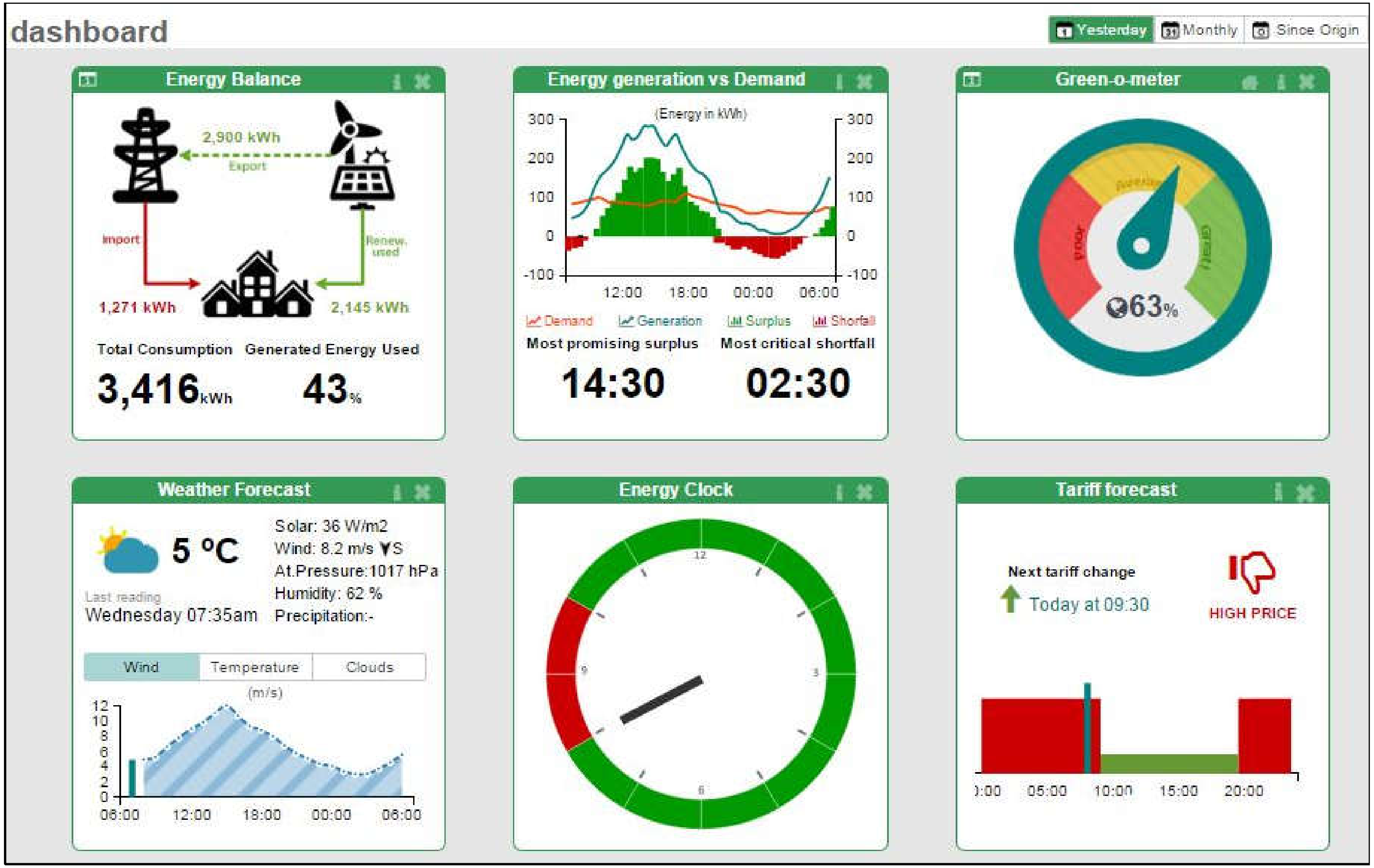
Corne et al, Heriot Watt University, MACS

(tuohy@esru.strath.ac.uk)

http://origin-concept.eu/

ORIGIN User Feedback: Web and Phone App

Behavioural Stimulus 3: Tariffs



(tuohy@esru.strath.ac.uk)

- DESIGN OF FUTURE GRID CONNECTED DISTRICT ENERGY NETWORKS WITH RENEWABLES, LOAD SHIFTING, AND STORAGE.

FINANCIALS IMPORT / EXPORT:

- Current costs can be summarized as: average import costs 11p/kWh, average export generates 5p/kWh without incentives and 15p/kWh including incentives.
- In this paper two simplified scenarios are used to bracket the possible financial frameworks, these are:
  - (i) a net metering (NM) scenario where imports and exports have equal value (here we use 11p/kWh), Needs Government Incentives.
  - (ii) a worst case (WC) scenario where the local grid attaches zero value to exports (import costs of 17p/kWh and export price of 0p/kWh), no value for export so curtailment of system.

- Performance metric: Levelized Cost of Energy

$$LCOE = C_{ann} / (\text{Local Load}) \quad (p/kWh)$$

- # DESIGN OF FUTURE GRID CONNECTED DISTRICT ENERGY NETWORKS WITH RENEWABLES, LOAD SHIFTING, AND **STORAGE**.

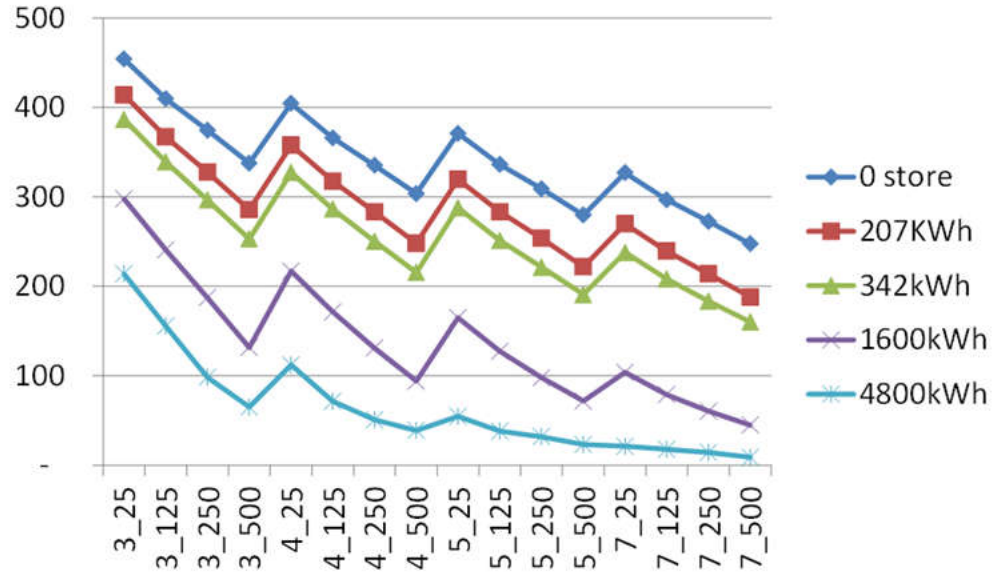
Addition of **storage**:

	Storage								
type:	none	FB 100	LA 96	LI 38	FB 400	LA 192	LI 100	FB 1600	FB 4800
nominal store (kWh):	0	100	518	380	400	1037	1000	1600	4800
available store (kWh):	0	100	207	342	400	415	900	1600	4800
Grid %	47%	44%	42%	39%	37%	39%	32%	30%	22%
NMCOE	7.6	8.2	9.1	9.3	9.9	10.2	11.8	13.7	23.5
WC COE	15.8	15.8	16.1	15.9	16.0	16.6	17.4	18.1	26.0
% RES Used	53%	56%	60%	61%	68%	65%	68%	79%	92%

- DESIGN OF FUTURE GRID CONNECTED DISTRICT ENERGY NETWORKS WITH RENEWABLES, LOAD SHIFTING, AND STORAGE.

Optimum? Autarky?

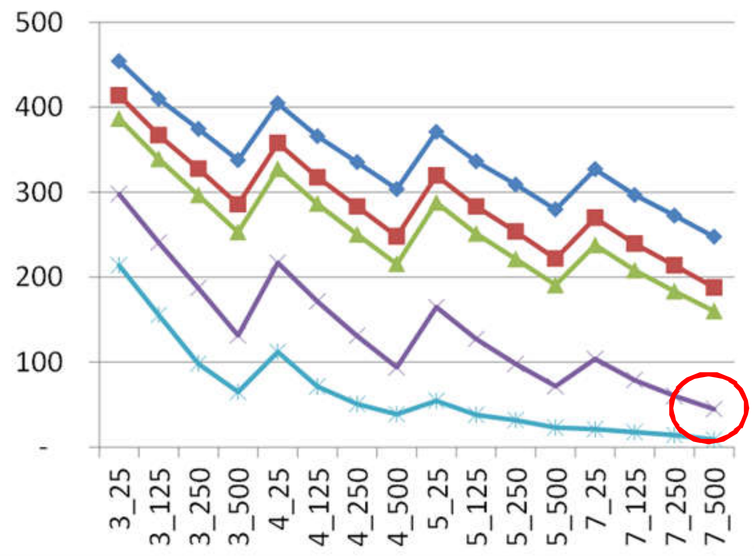
GRID MWh pa	Storage				
WT_PV	0	207KWh	342kWh	1600kWh	4800kWh
3_25	454	414	386	298	214
3_125	410	367	339	240	155
3_250	374	327	296	187	98
3_500	338	286	253	132	65
4_25	404	358	327	217	112
4_125	366	317	286	171	71
4_250	335	283	250	131	51
4_500	303	248	215	94	39
5_25	371	320	288	165	54
5_125	336	283	251	127	38
5_250	309	253	221	98	32
5_500	280	222	191	72	23
7_25	327	270	238	104	21
7_125	297	239	208	79	18
7_250	272	214	183	60	14
7_500	247	188	160	45	9

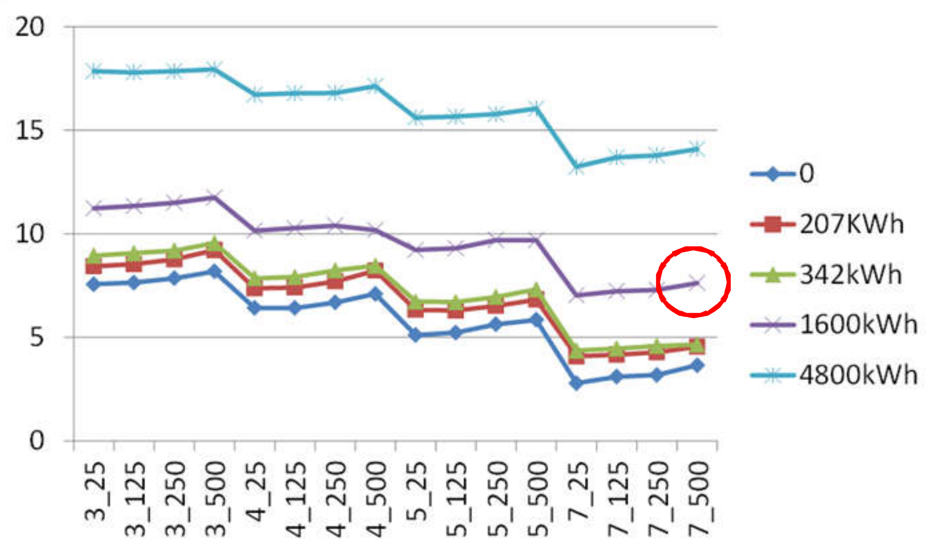


Grid imports in MWh p.a. (y-axis) for generation and storage combinations. On the x-axis '3_25' = 3 225kW WT and 25kWp PV etc.

- DESIGN OF FUTURE GRID CONNECTED DISTRICT ENERGY NETWORKS WITH RENEWABLES, LOAD SHIFTING, AND STORAGE.

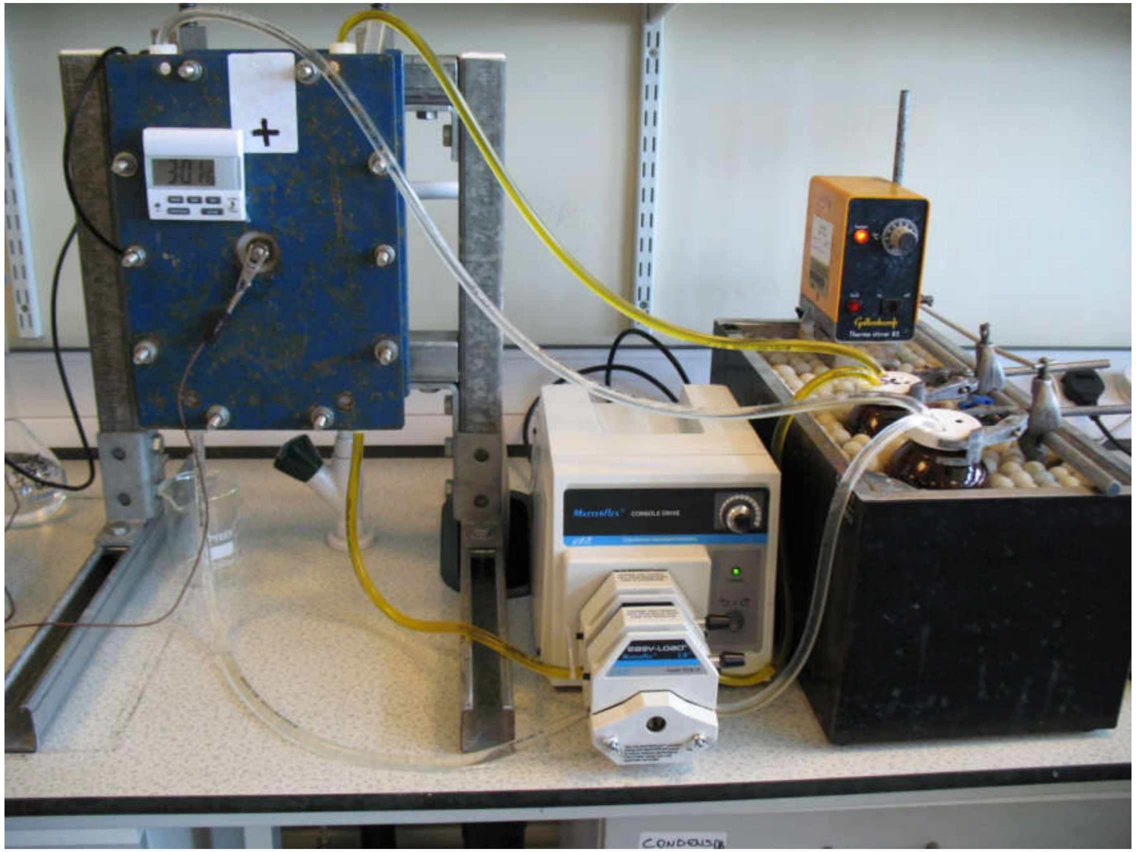
Optimum? Autarky and Costs?





Reduce Grid dependence 47% to 4% for same 7.6 p/kWh NM COE as current costs.


Caution
Danger



Lotte Chemical 25 kW/50 kWh Flow Battery system

Lotte Chemical 250 kW/500 kWh Flow Battery system

THANK YOU FOR YOUR ATTENTION

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