Design and optimization of a small compressed air energy storage system for isolated applications

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Outline

- ❖ Motivations
- ❖ Research methodology
- ❖ Hybrid system design & modeling
- ❖ System performance Assessment
- ❖ Summary and conclusion

Motivations

- ❖ Reducing the fossil fuel consumption for isolated loads.
  - ➢ Environmental Impact
  - ➢ Difficulty of fuel delivery in winter
- ❖ CAES system to support the wind based energy system
  - ➢ Random nature of the wind energy
  - ➢ Economical and technical challenges
- ❖ Cost effective design of a wind based energy system.
  - ➢ Increase the harvested energy from the available wind energy
  - ➢ Enhance the reliability and economical feature of RES

Research methodology

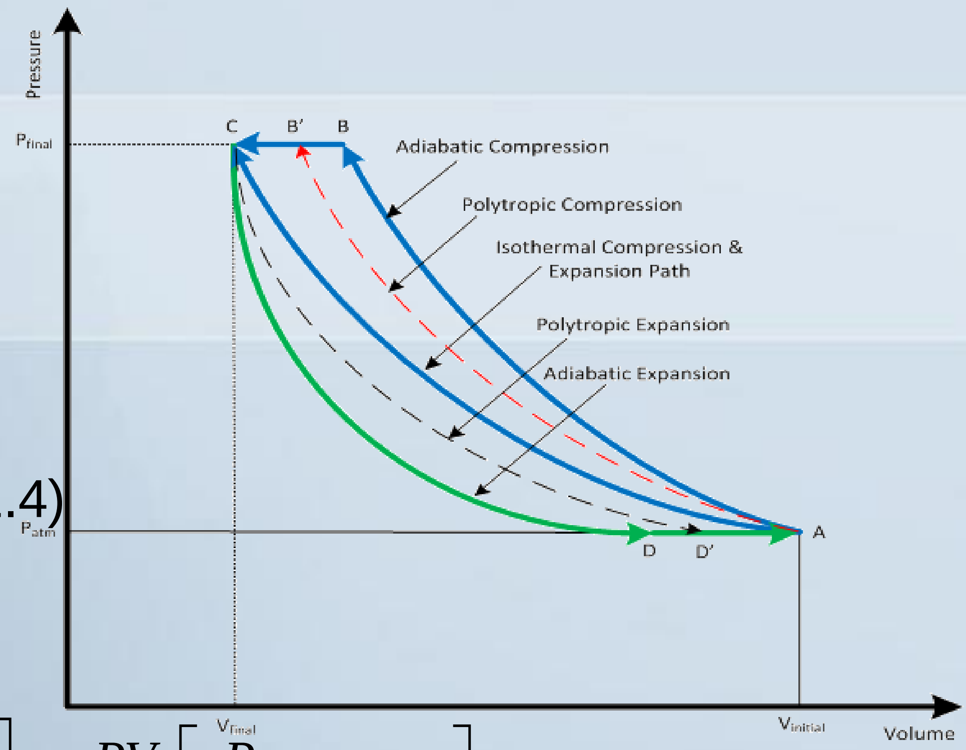
- Develop a hybrid configuration
- CAES system component modeling
- Wind and load data generation
- Evaluate the performance of different energy storage systems

Energy Conversion in CAES

❖ Charging or discharge cycles

➢ Isothermal

$$W_{isothermal} = -\int_{V_1}^{V_2} P\,dV = P_1V_1 ln(\frac{P_2}{P_1})$$

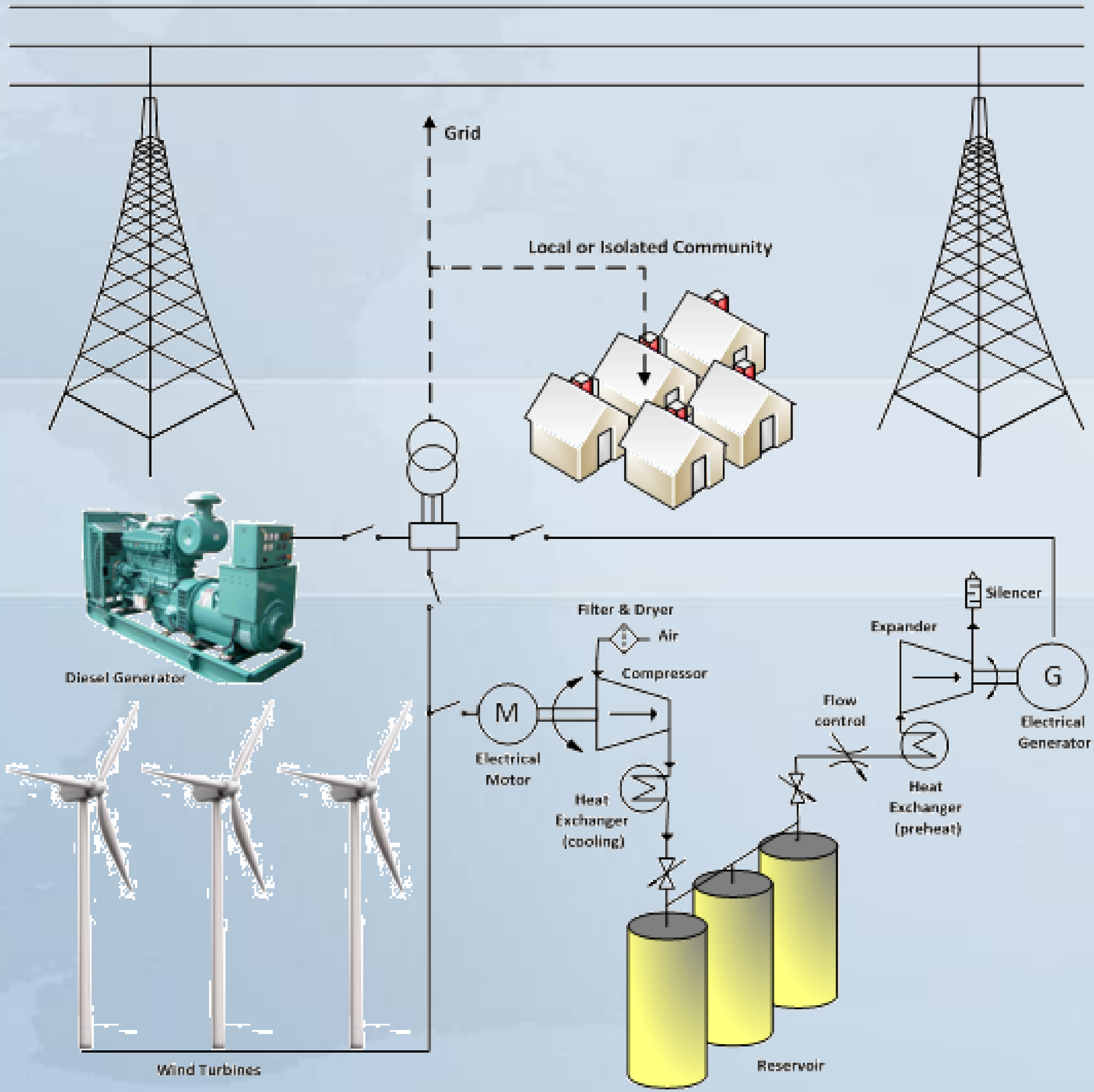


➢ Polytrophic (1<n<1.4)

➢ Adiabatic (n=1.4)

$$W_{Polytropic} = \frac{nP_1V_1}{n-1}\left[(\frac{V_1}{V_f})^{n-1} - 1\right] = \frac{nP_1V_1}{n-1}\left[(\frac{P_2}{P_1})^{(n-1)/n} - 1\right]$$

Hybrid wind-diesel-CAES system



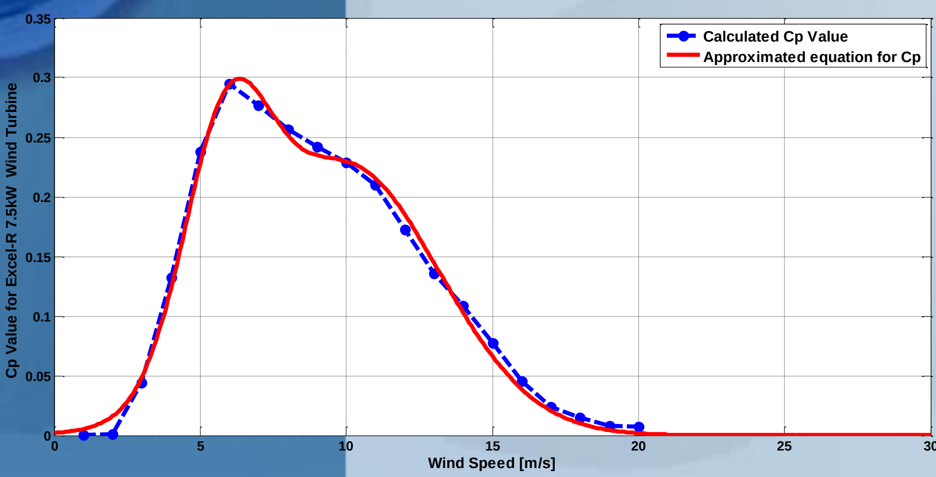
Wind turbine modeling

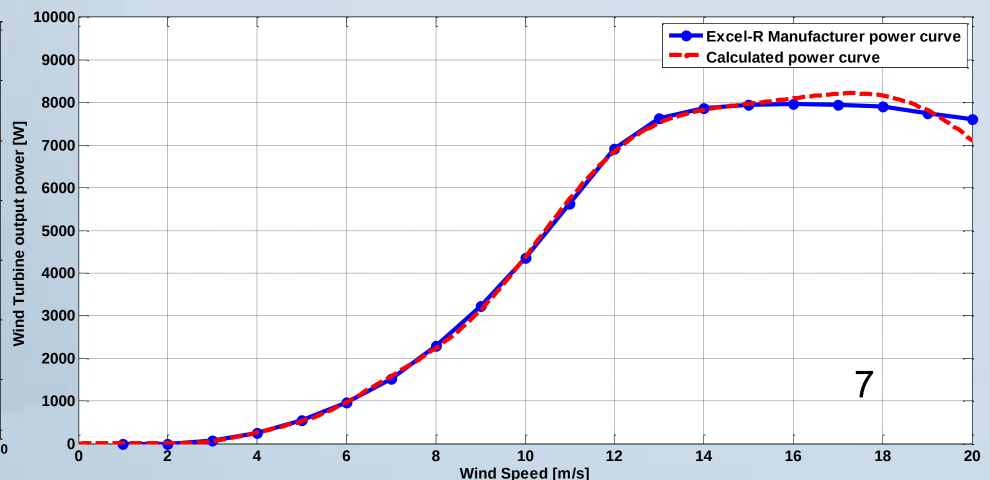
- ❖ Wind turbine

$$P_{wind\ Turbine} = 0.5\ C_p(V_w)\ \rho\ A_r\ V_w^{\ 3}$$

- ❖ Power Curve
  - ➢ Datasheet
  - ➢ Approximation

$$C_p(V_w) = a_1 e^{(\frac{V_w - b_1}{c_1})^2} + a_2 e^{(\frac{V_w - b_2}{c_2})^2} + a_3 e^{(\frac{V_w - b_3}{c_3})^2} + a_4 e^{(\frac{V_w - b_4}{c_4})^2}$$





CAES System components

❖ Compressor

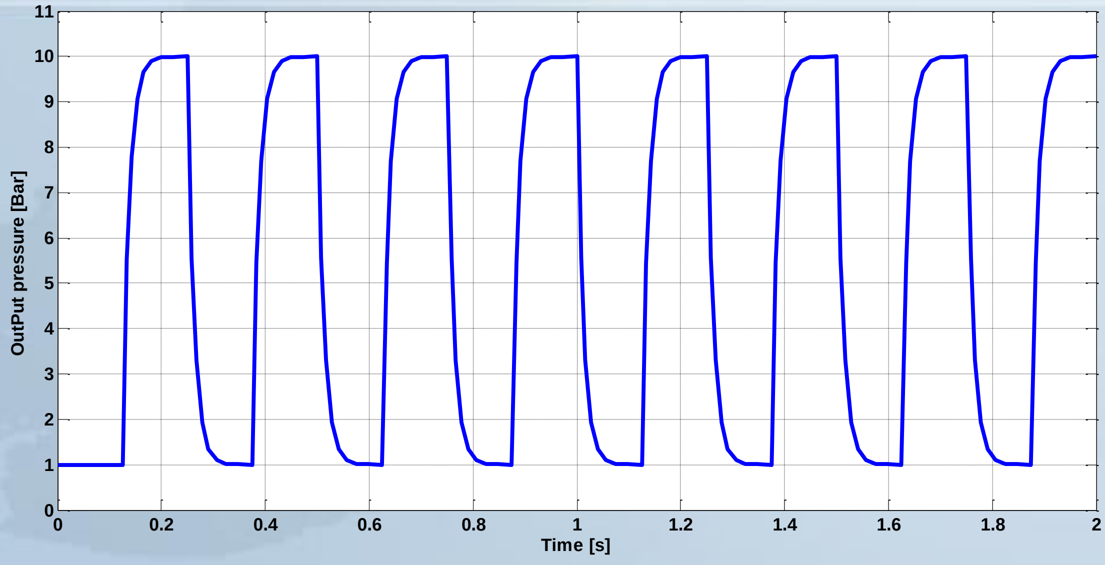
$$P_{Comp} = \left(\frac{n}{n-1}\right).P_{in}\ Q_{Comp}\left[PR^{(\frac{n-1}{n})} - 1\right]$$

$$Q_{Comp} = \frac{(n-1)P_{Comp-Nstage}}{nN_{CS}P_{in}(PR^{(\frac{n-1}{nN_{CS}})} - 1)}$$

$$m_{out-Comp} = \rho.\int Q_{Copm}.dt$$

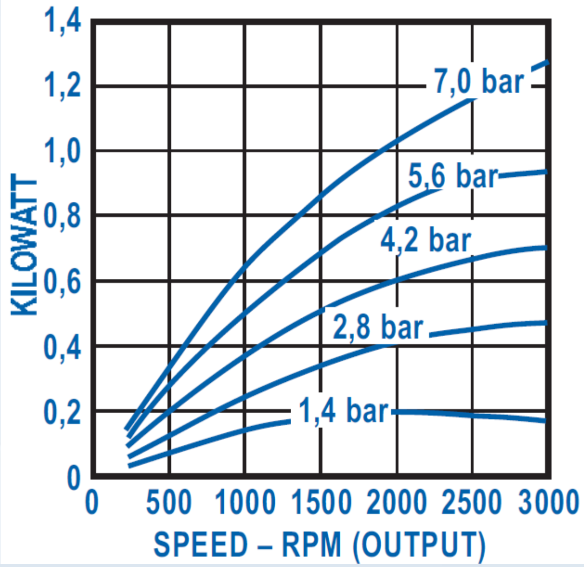
$$P.V^{n} = mRT$$

$$P_{comp-out}(s) = \frac{K_{Comp}}{J_{T-Comp}s + B_{T-Comp}} P_{in}(s)$$

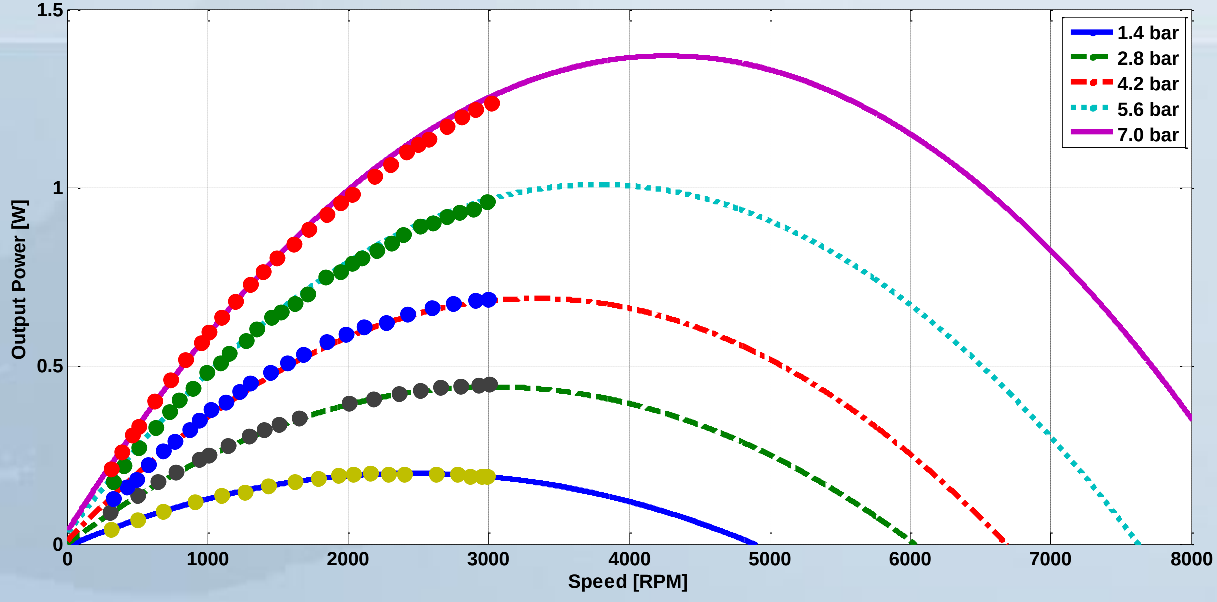


Air Motor

- Steady state model



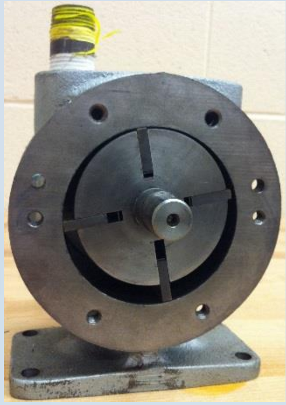
$$P_{mAM}(n_{AM}, p_{AM}) = C_{PW2}(p_{AM})n_{AM}^2 + C_{PW1}(p_{AM})n_{AM} + C_{PW0}(p_{AM})$$

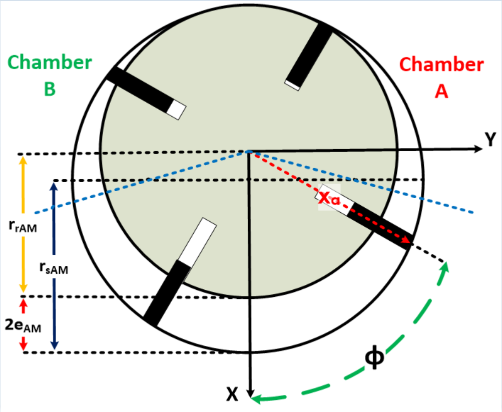


Air Motor Cont.

❖ Dynamic model

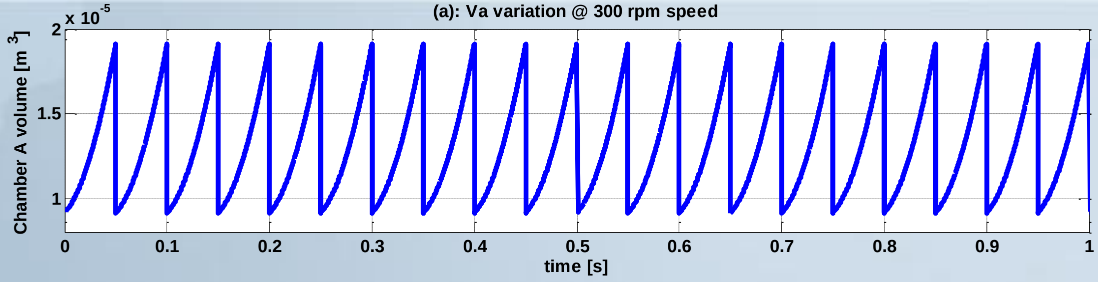
➢ Volume change

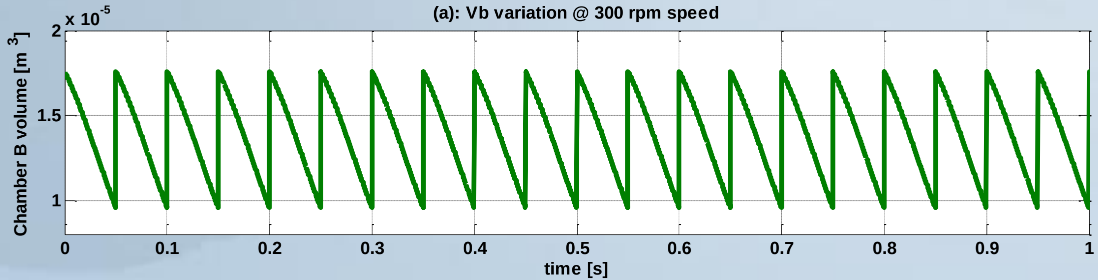




$$V_a(\phi) = \frac{1}{2} L_{AM} (r_{sAM}^2 - r_{rAM}^2)(\pi + \phi) + \frac{1}{4} L_{AM} e_{AM}^2 sin2\phi + L_{AM} e_{AM} r_{sAM} sin\phi + c$$

$$V_b(\phi) = \frac{1}{2} L_{AM} (r_{sAM}^2 - r_{rAM}^2)(\pi - \phi) - \frac{1}{4} L_{AM} e_{AM}^2 sin2\phi - L_{AM} e_{AM} r_{sAM} sin\phi + c$$



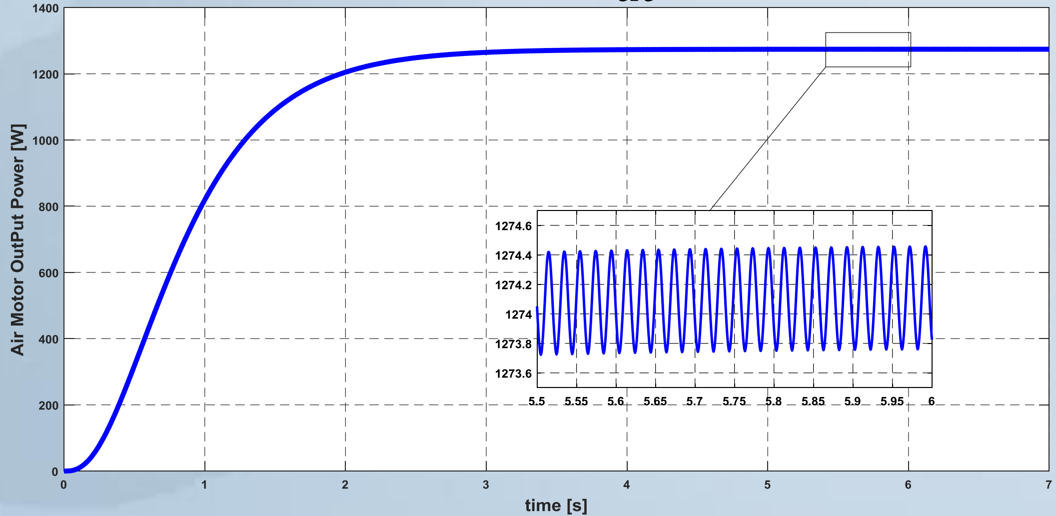


Air Motor Cont.

- Dynamic Model
  - Pressure change

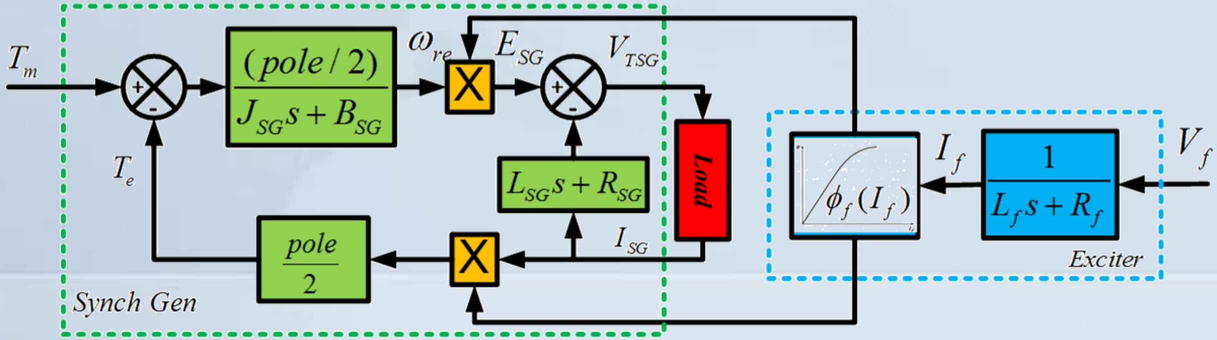
$$\frac{dP_a}{dt}=\frac{R\,k\,T_s}{V_a}\frac{dm_a}{dt}-\frac{kP_a}{V_a}\frac{dV_a}{dt} \qquad \frac{dP_b}{dt}=\frac{R\,k\,T_s}{V_a}\frac{dm_b}{dt}-\frac{kP_b}{V_b}\frac{dV_b}{dt}$$

  - Developed Torque $T_{AM}(P_a,P_b,\phi)=(P_a-P_b)(x_a^2-r_{rAM}^2)\frac{L_{AM}}{2}$
  - Air motor Drive train $J_{AM}\frac{d\omega}{dt}+B_{AM}\omega=T_{AM}-T_d$



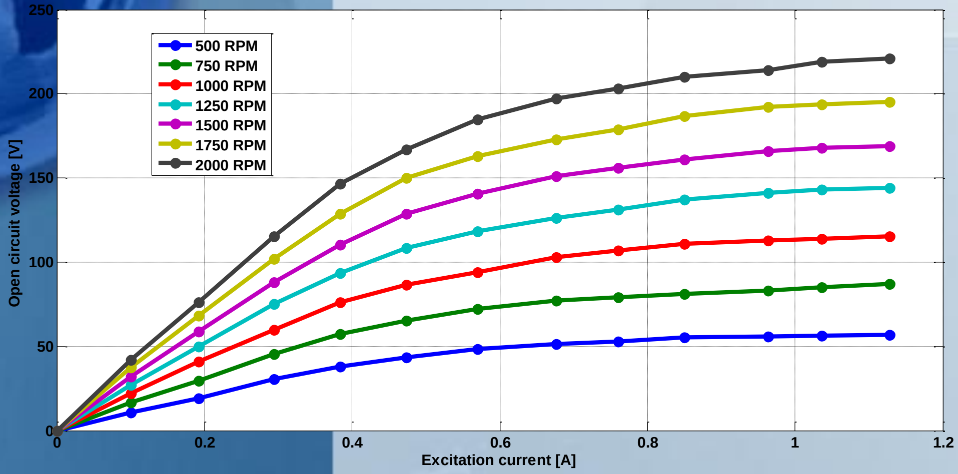
Synchronous Generator

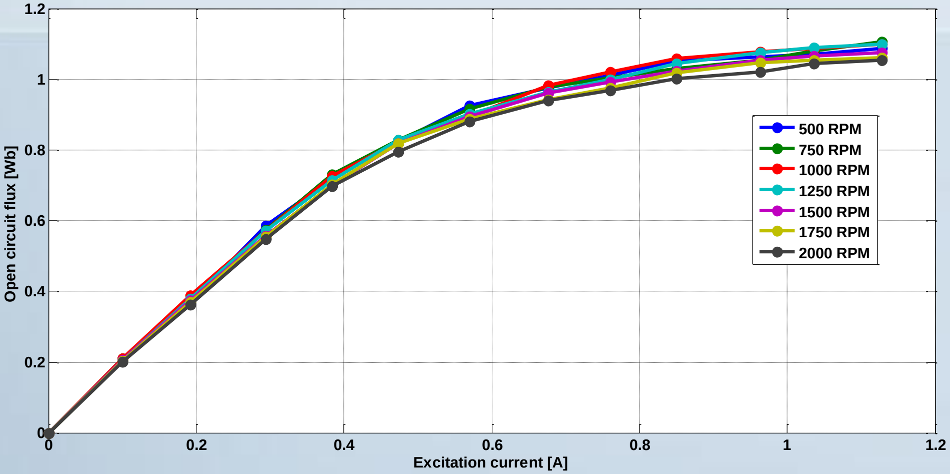
- Block diagram



- Experimental test results

$$E_{SG}(I_f,\omega_{re}) = K_{SG}\phi(I_f)\omega_{re}$$

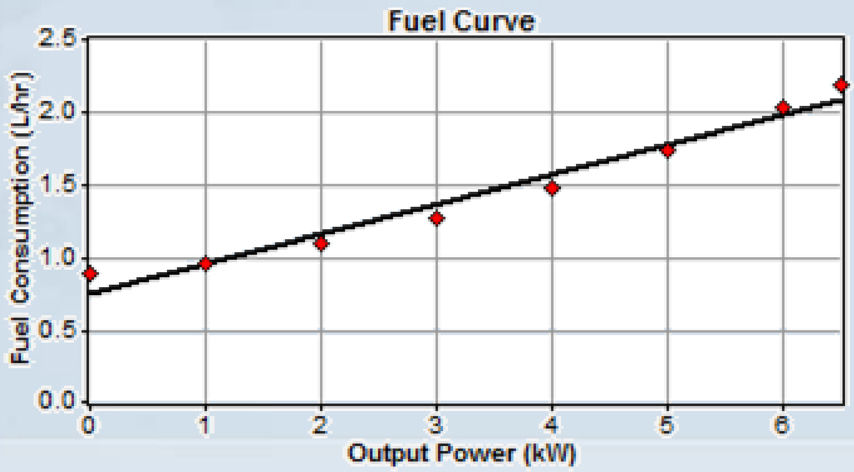




$$\phi(I_f) = 0.4545(I_f)^3 - 1.911(I_f)^2 + 2.554I_f - 0.01824$$

Diesel Generator

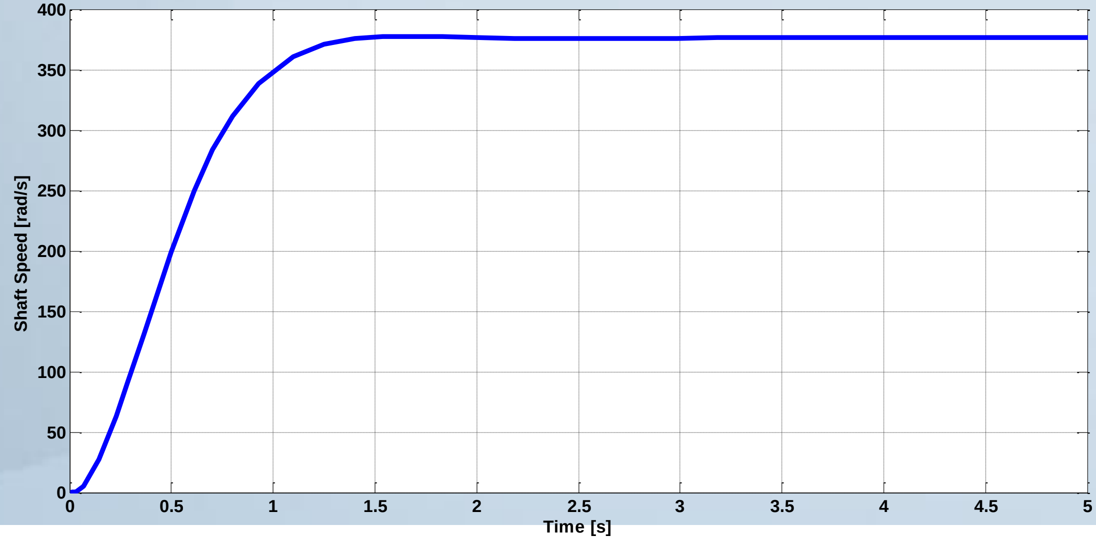
➢ Fuel consumption



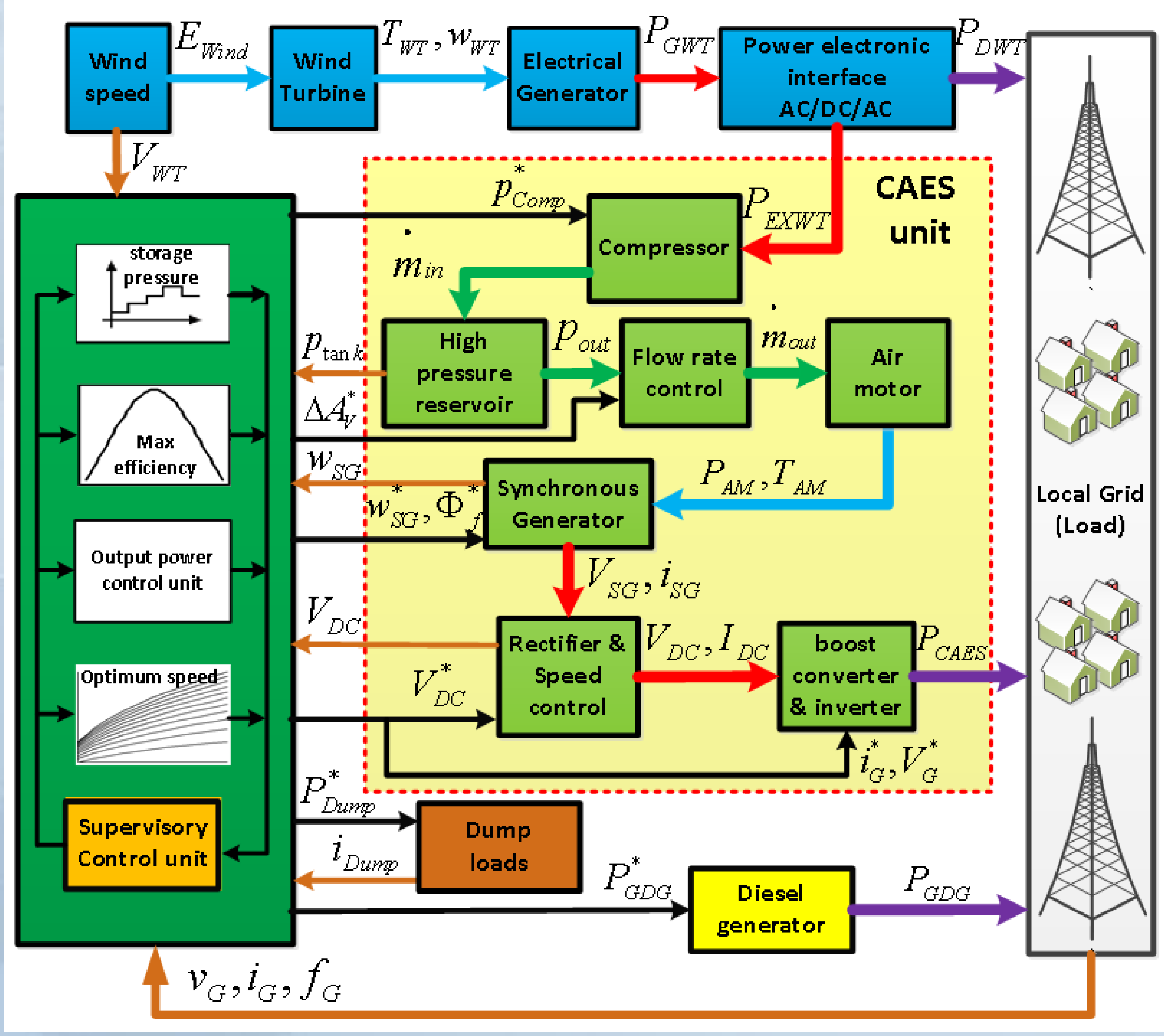
$$FC_{DG} = (2.15\times10^{-8})P_{DG}^{2} + (6.29\times10^{-5})P_{DG} + 0.8782$$

❖ Dynamic model

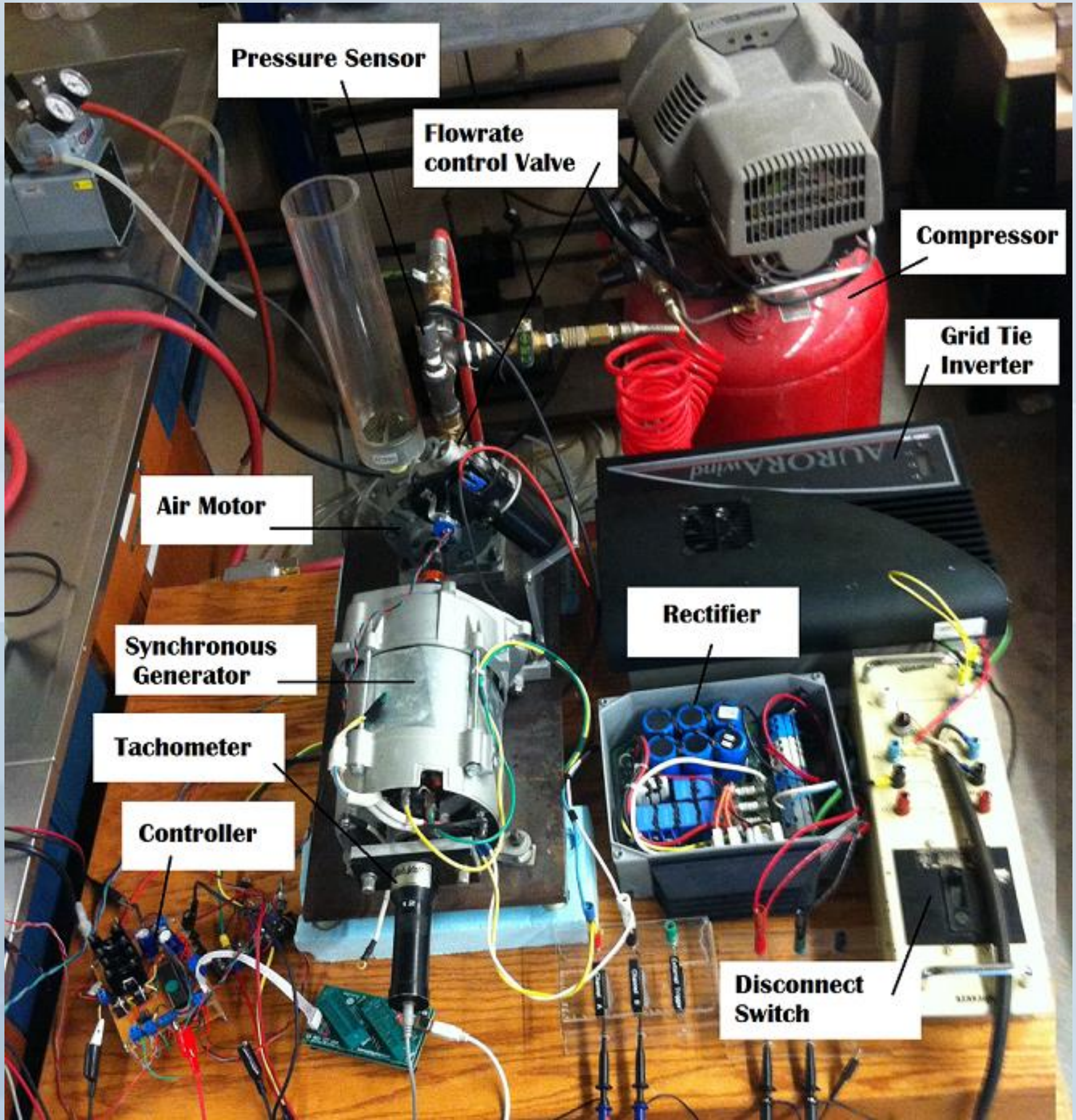
$$\omega_{rDG}(s) = \frac{1}{J_{DG}s + B_{DG}}[T_{mDG}(s) - T_{d}(s)]$$



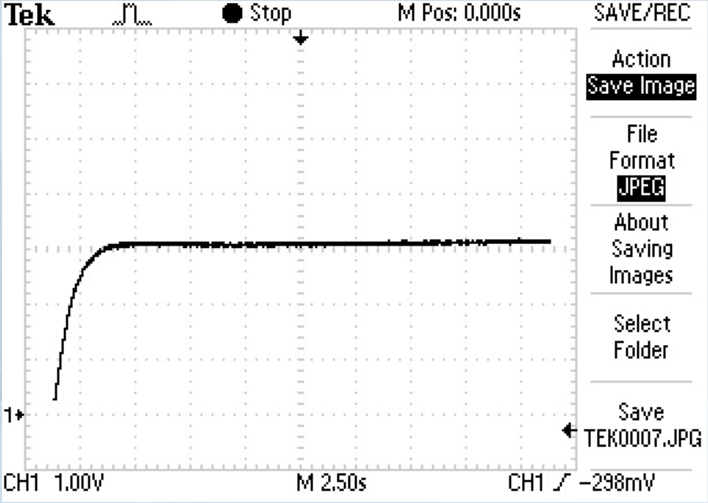
Supervisory Control Unit

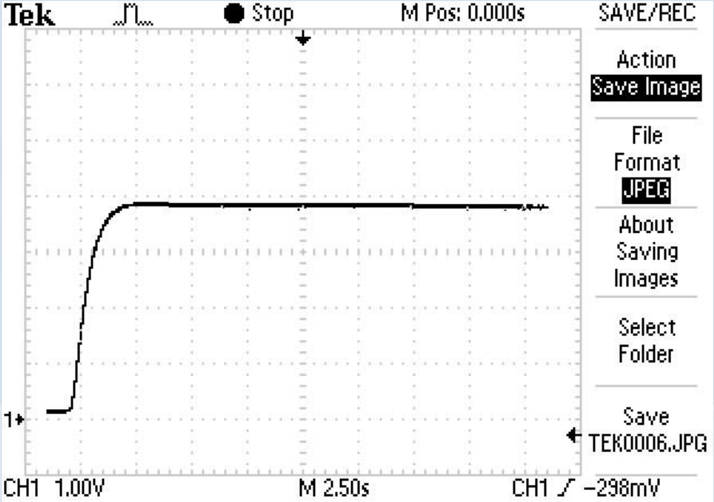


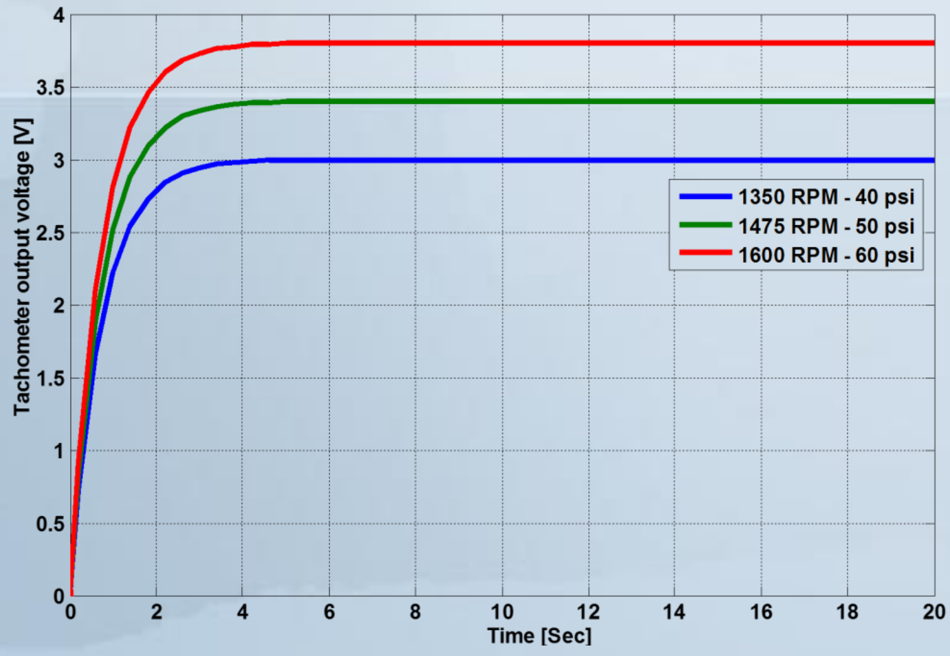
Experimental Setup



Air motor model validation



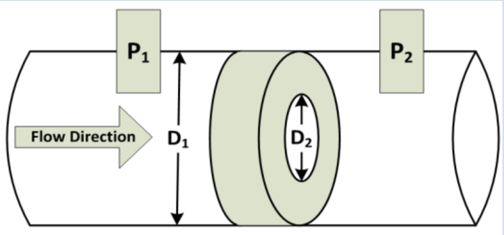




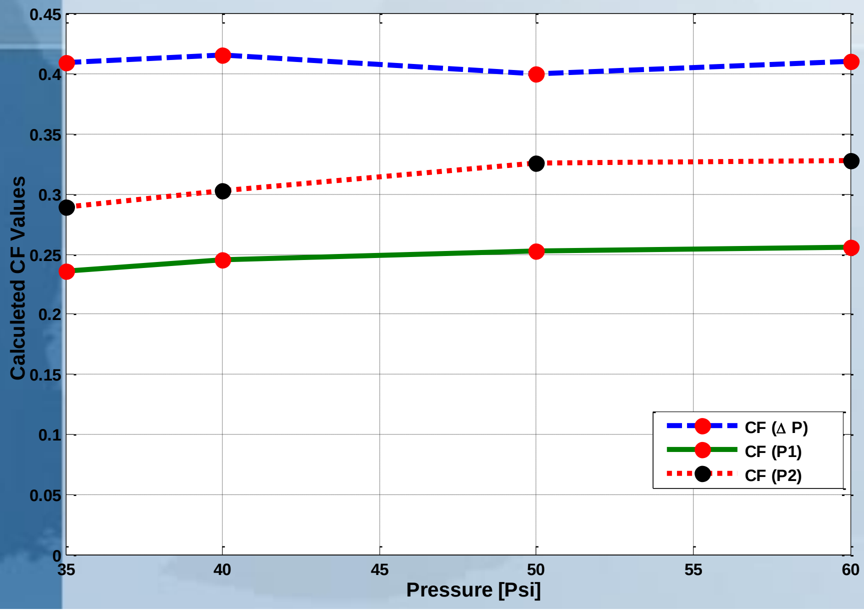
Flow rate valve model

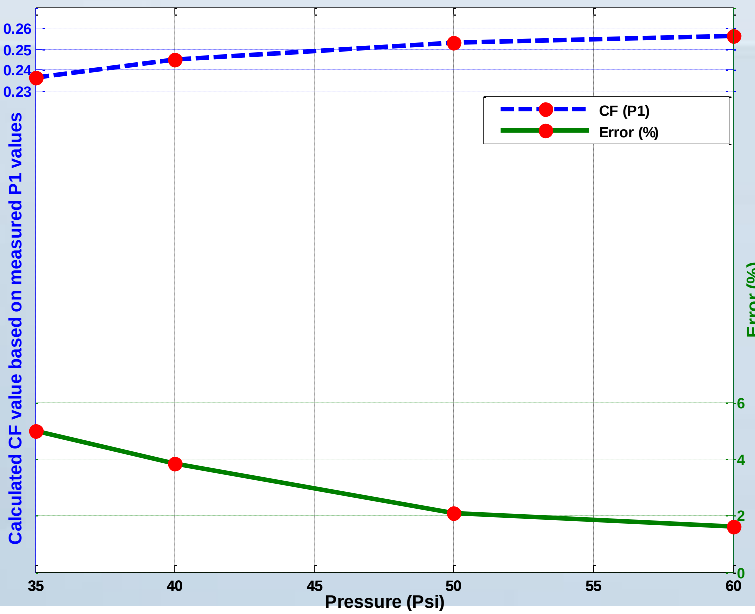
- Flow coefficient

P$_1$ (Psi)	35	40	50	60
P$_2$ (Psi)	28.200	31.560	35.860	42.275
Speed (rpm)	1150	1350	1475	1600
Output Flow rate (CFM)	30.448	35.301	42.879	49.195
Air consumption based on Datasheet (CFM)	29	34	42	50
Error (%)	4.992	3.825	2.094	1.610
C_f value based on $\Delta P=P_1-P_2$	0.410	0.416	0.401	0.411
C_f value based on $\Delta P=P_1-P_{atm}$	0.236	0.245	0.253	0.256
C_f value based on $\Delta P=P_2-P_{atm}$	0.289	0.303	0.326	0.328

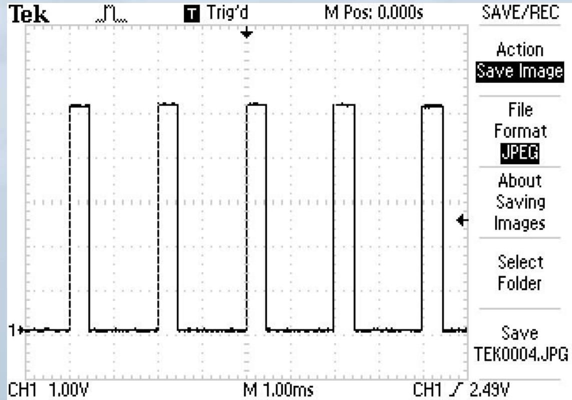


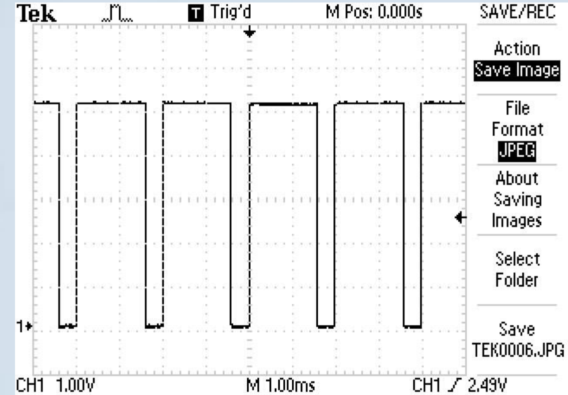
$$Q = C_f A_0 \sqrt{\frac{2\Delta P}{\rho}}$$

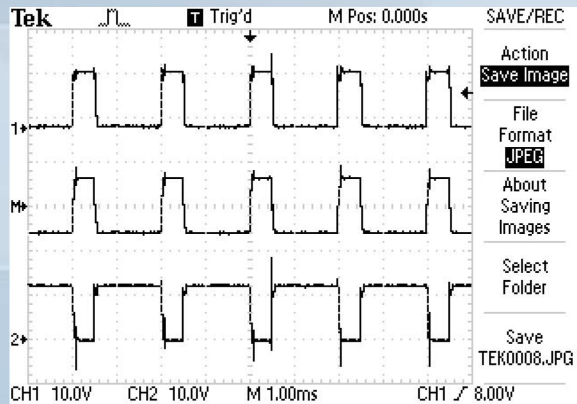


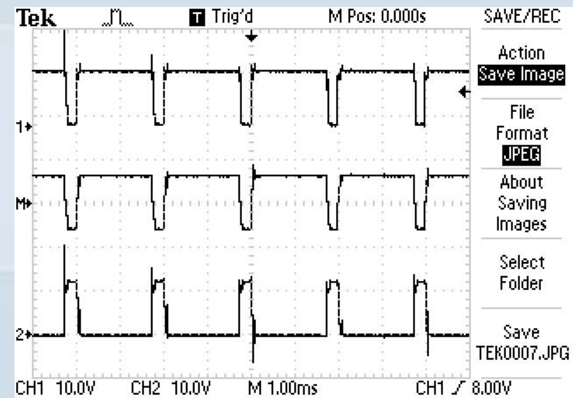


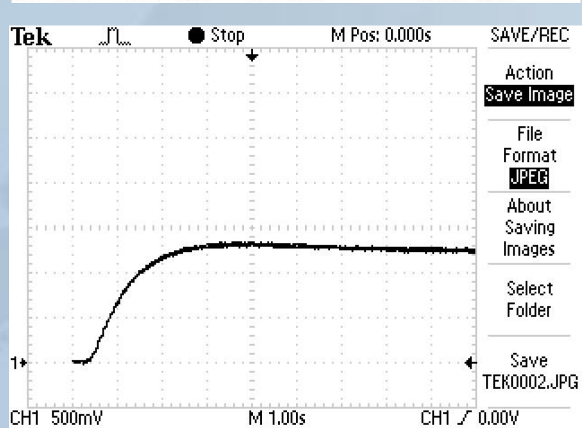
Flow rate control

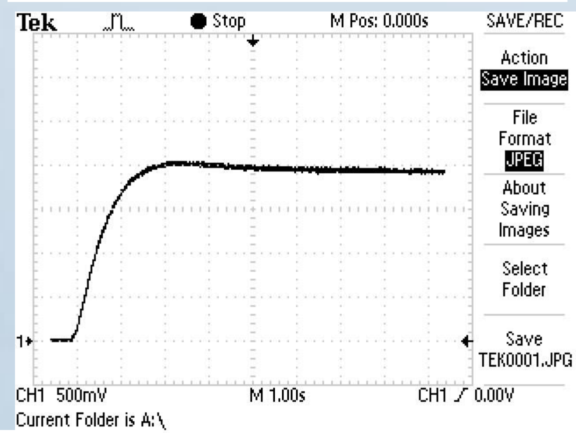






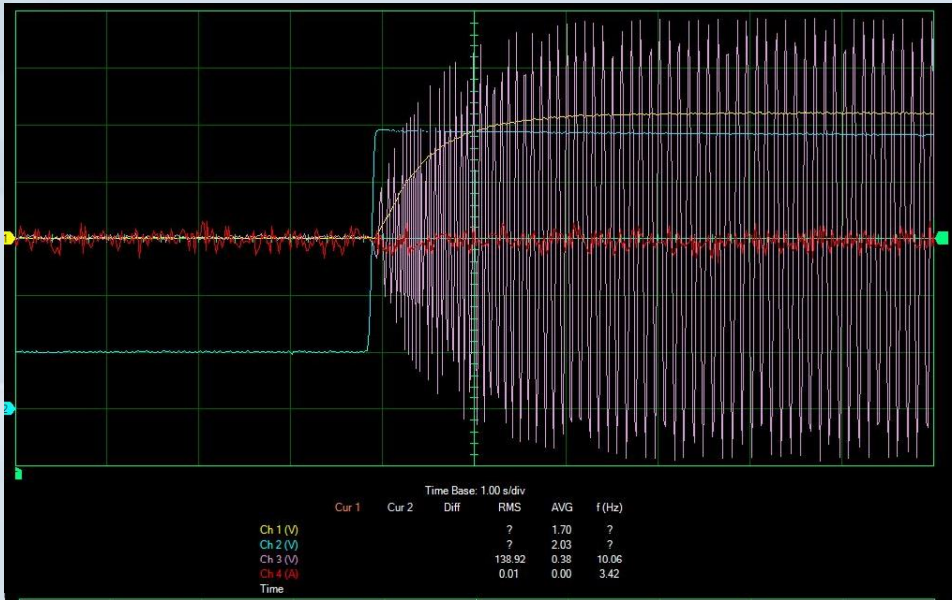




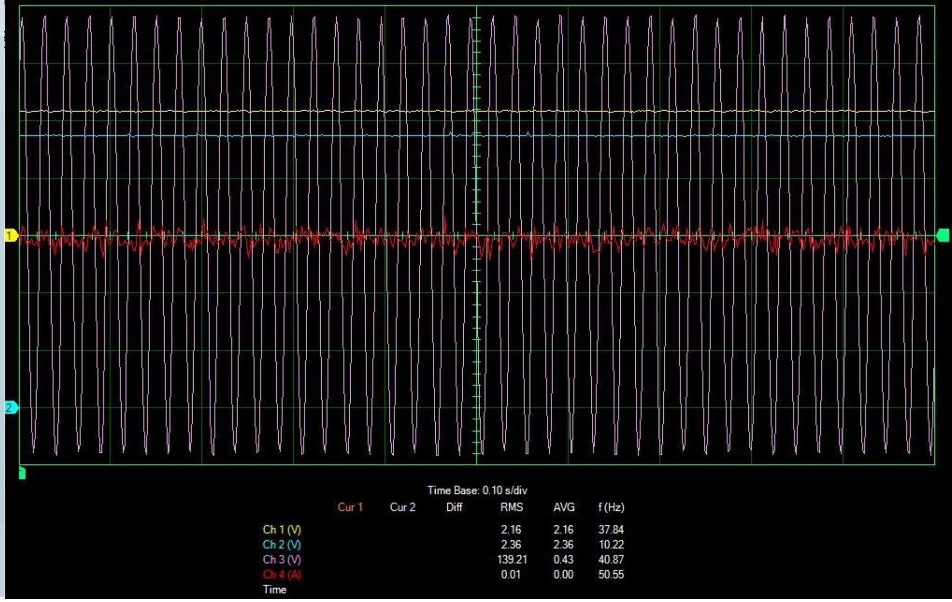


CAES system power control

- Dynamic

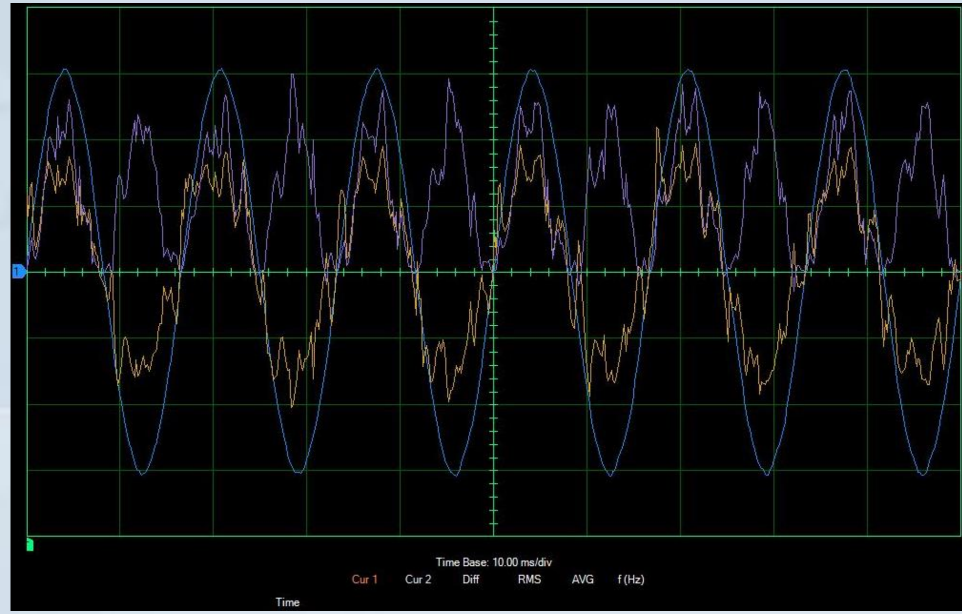


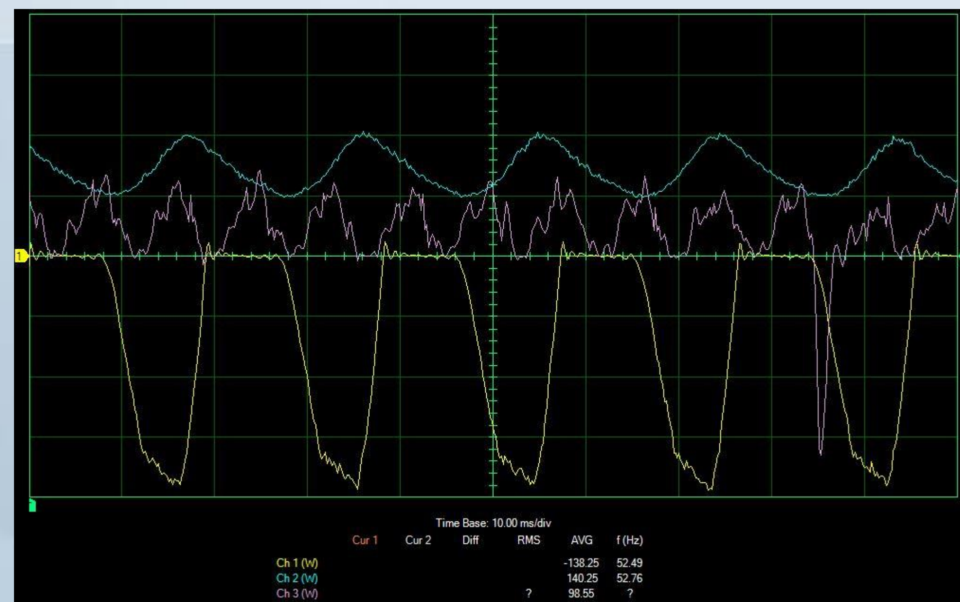
- Steady state



CAES system power control

- Output voltage,
- current and
- power





Hybrid system design optimization

Impact of

- ❖ Wind turbine selection
- ❖ Energy storage system rating
- ❖ Control strategy
- ❖ Energy storage type

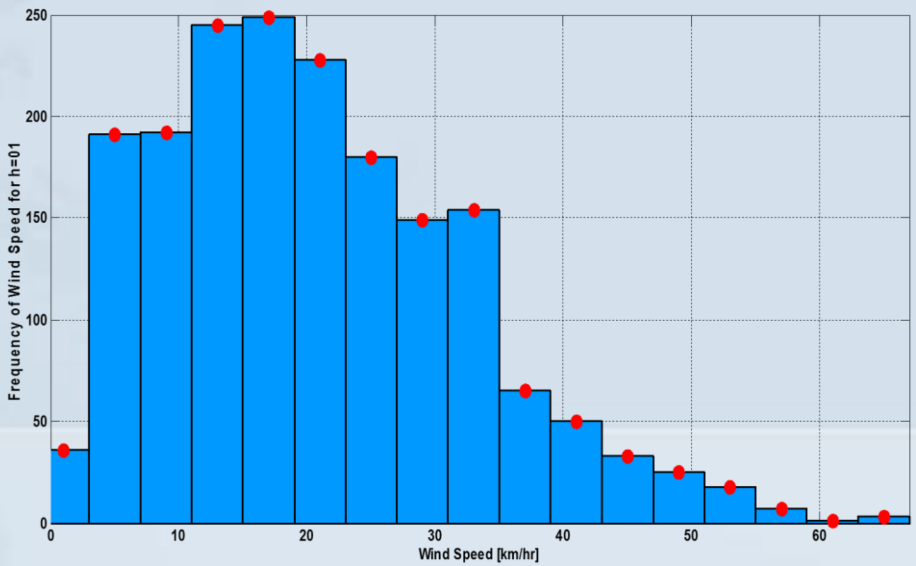
on total fuel consumption in an isolated application

Wind speed databases

- Available Wind data (1hr averaged)
  - Limited accuracy
  - Limited resolution.
  - Unreliable prediction of wind farm output power

- ✓ Standard statistical methods to
  - ✓ regenerate wind speed data with desired time resolution.
  - ✓ Combining multiple databases

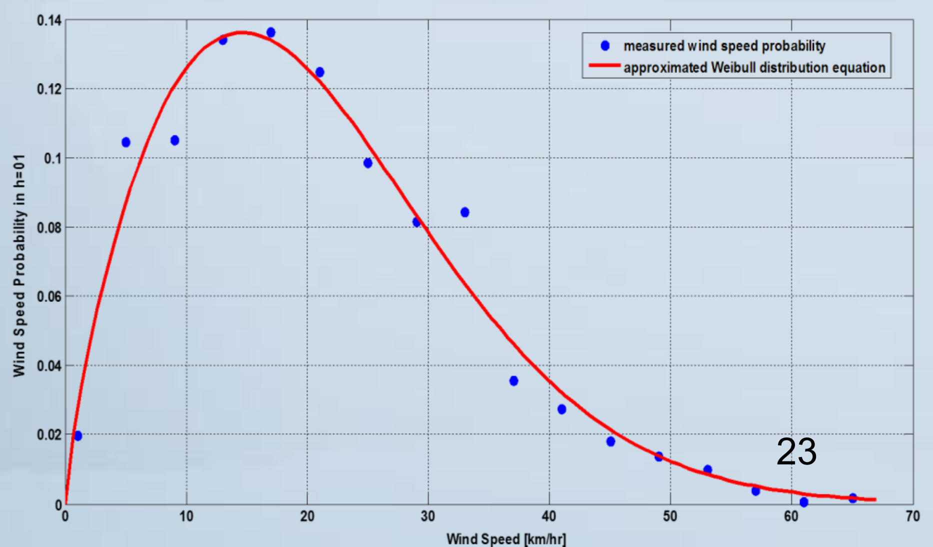
Wind speed distribution



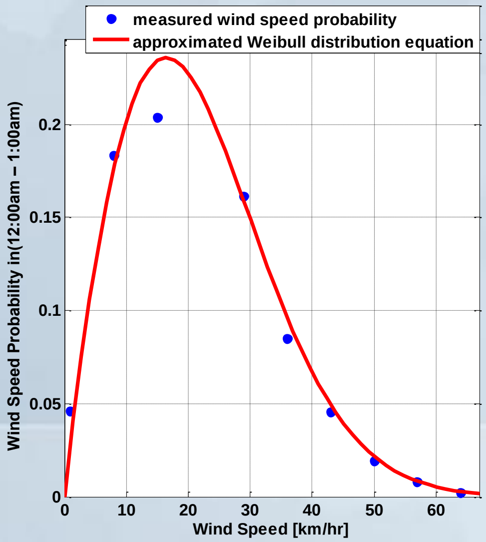
❖ Weibull probability distribution

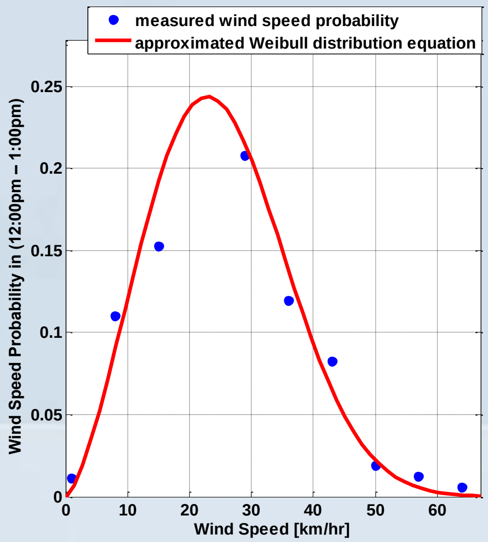
$$f(V) = \frac{k}{C}\left(\frac{V}{C}\right)^{k-1} e^{-\left(\frac{V}{C}\right)^{k}}$$

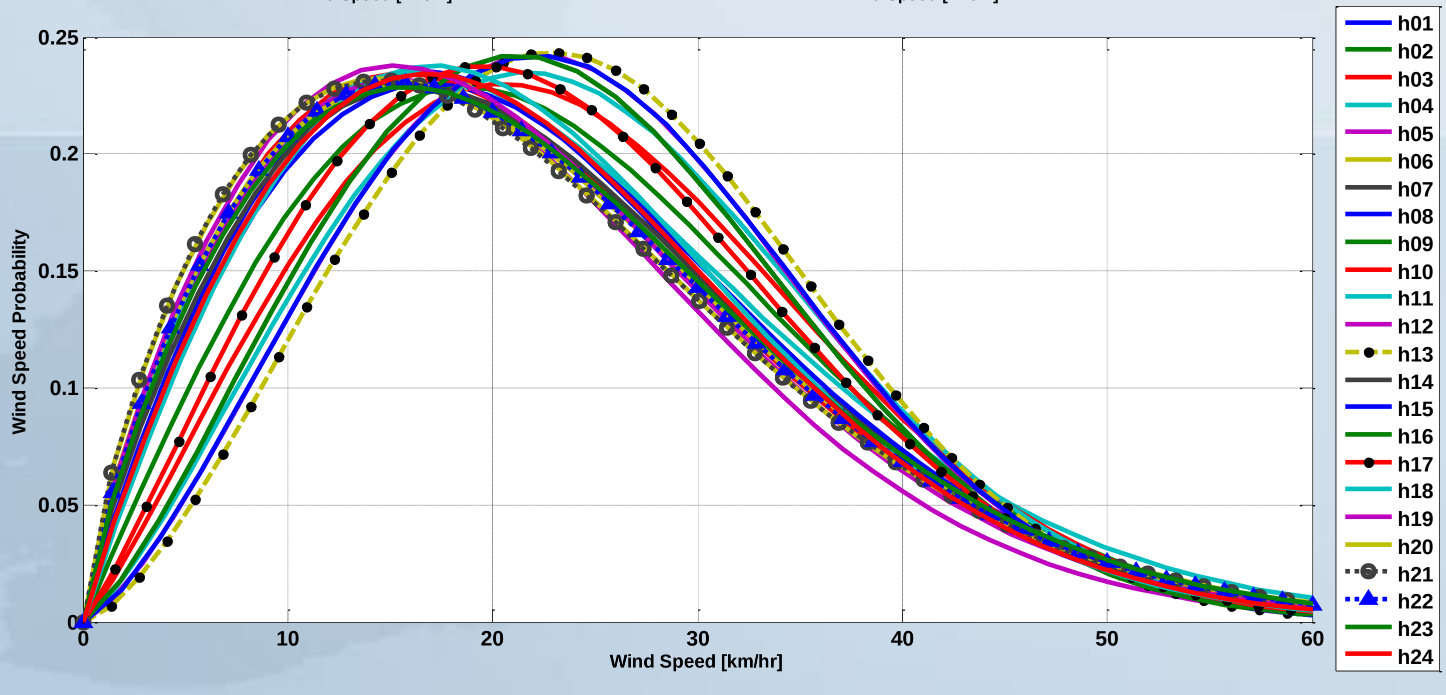
c is the scale factor
k is shape factor



Wind speed frequency distribution







Monte Carlo simulation

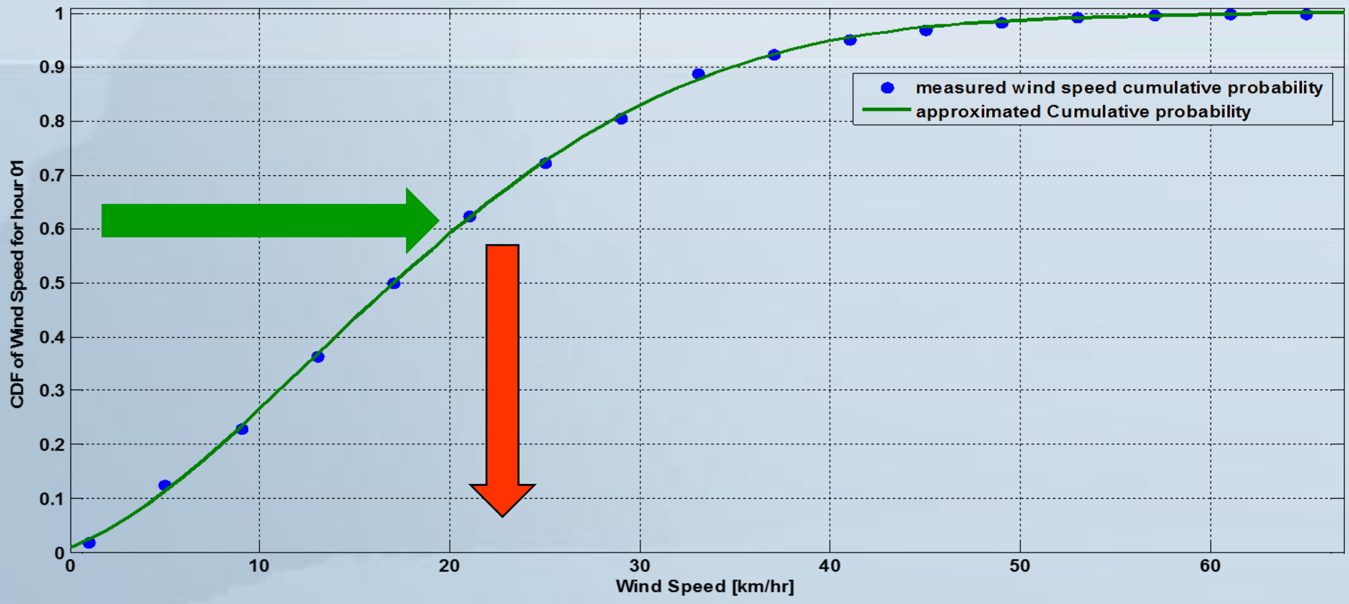
- Iteration process based on a specific probability distribution function.

- Monte Carlo simulation error = *1/√n (more than 1500 samples will result in less than 2.5% error)*

- Direct sampling method was applied to the Monte Carlo simulation

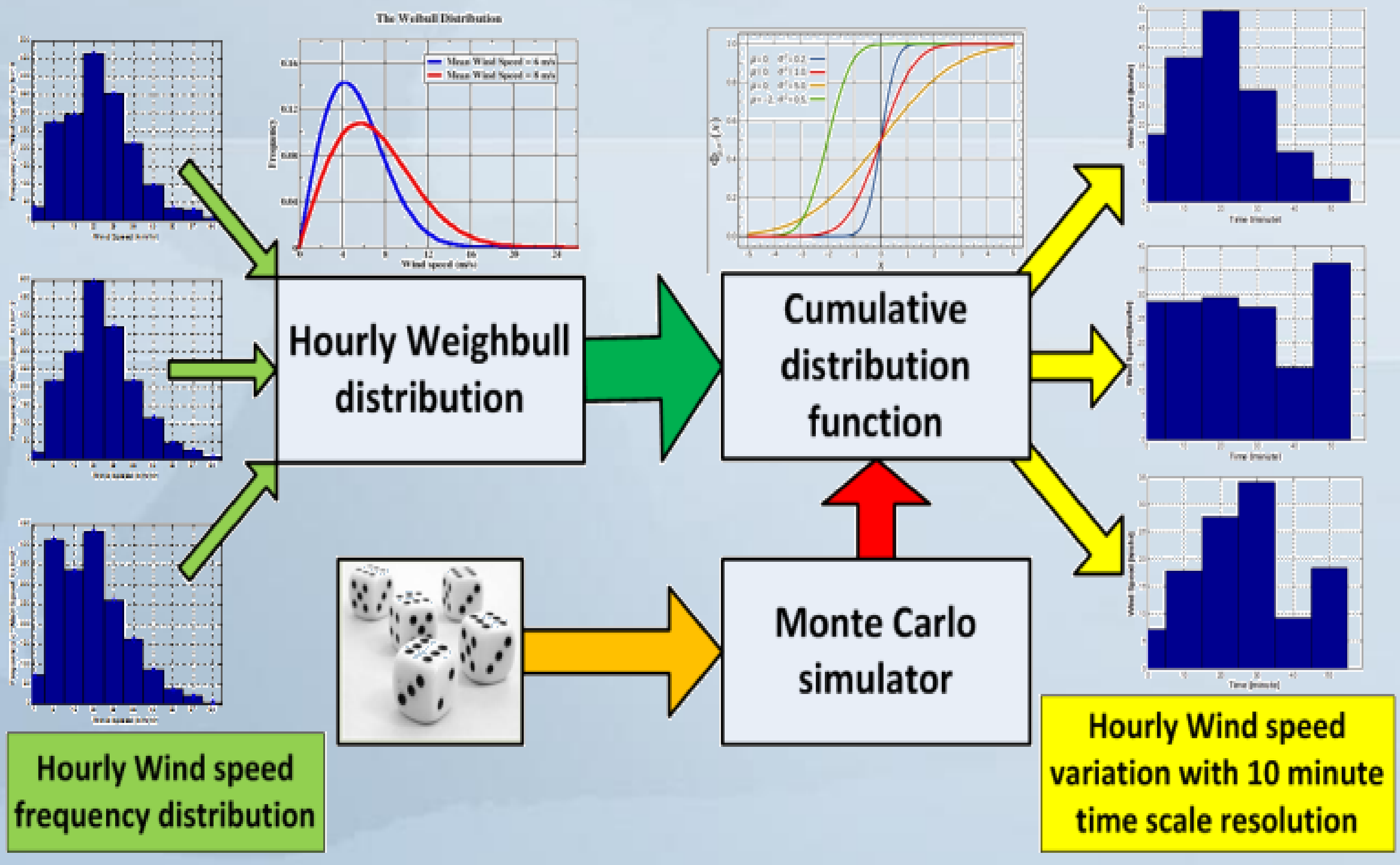
Monte Carlo simulation, Cont.

- A set of 1500 uniformly distributed numbers between [0-1] was produced and applied to the inverse of the Weibull Cumulative Distribution Function of each hour



Monte Carlo simulation, Cont.

- Proposed Method configuration



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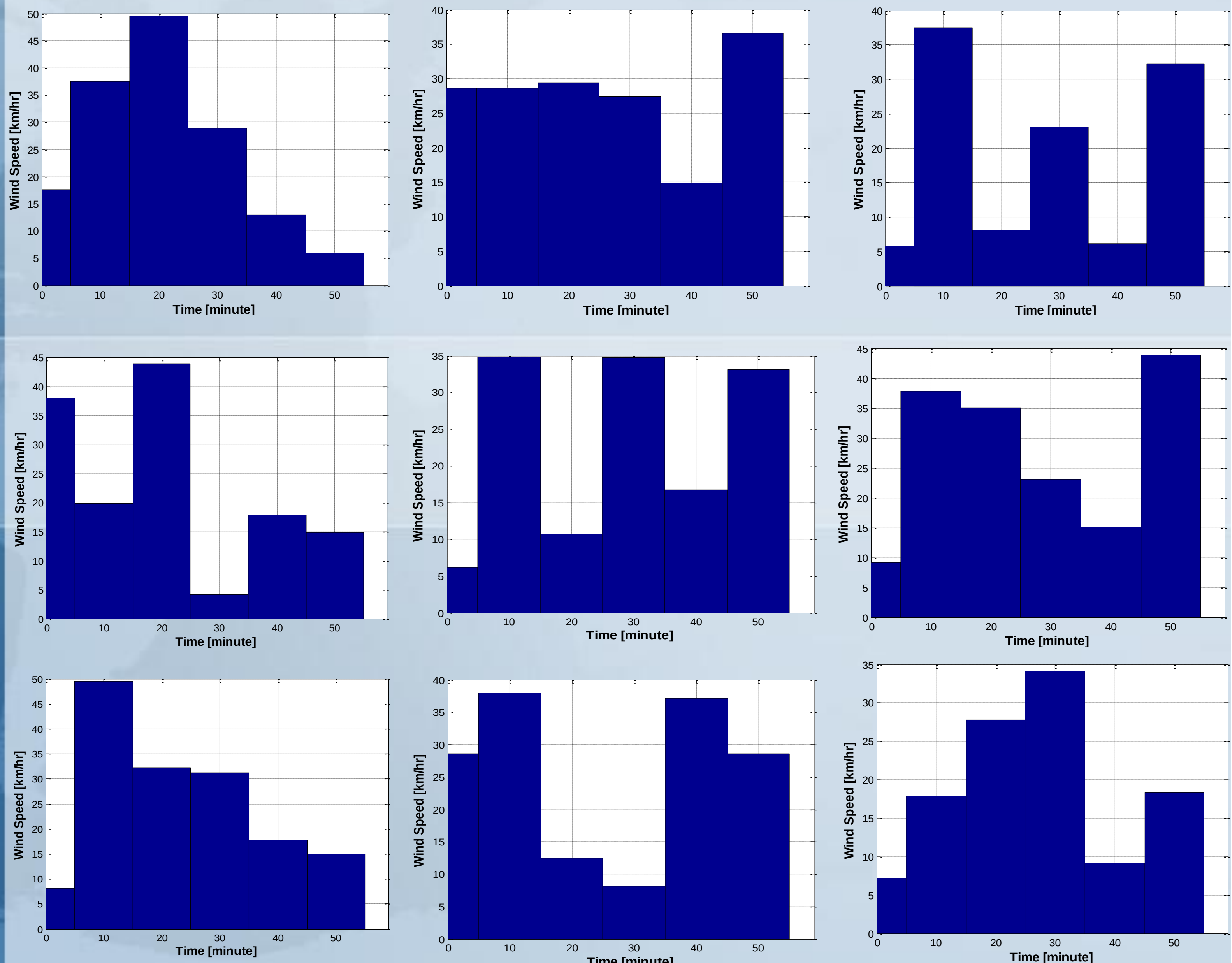
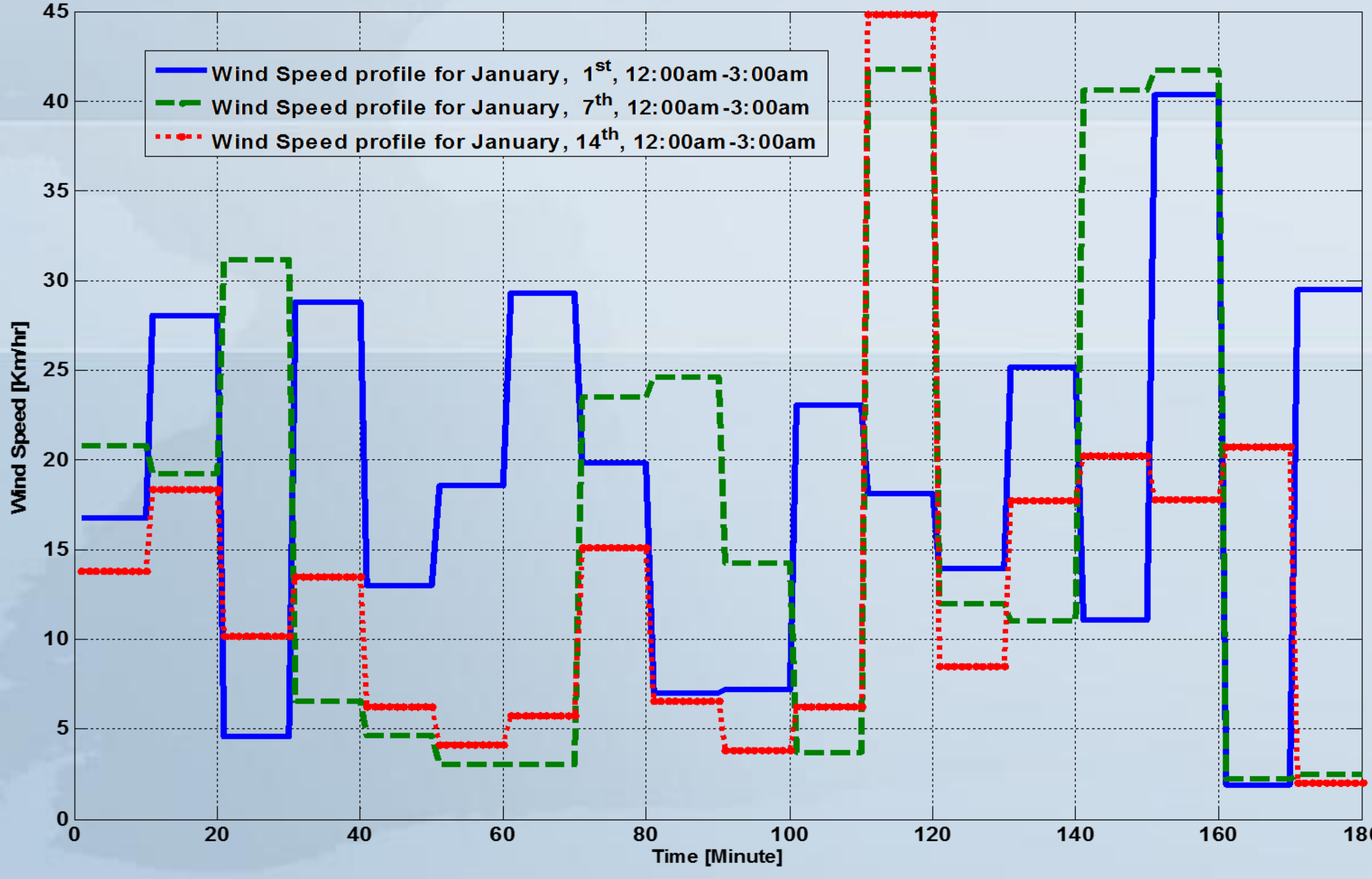
Wind Speed profile regeneration



Sample generated wind profile

- first 3 hours (12:00 am – 3:00 am) in 3 days (1st, 7th and 14th) in January with 10 minute resolution



Mathematical model of Wind turbine

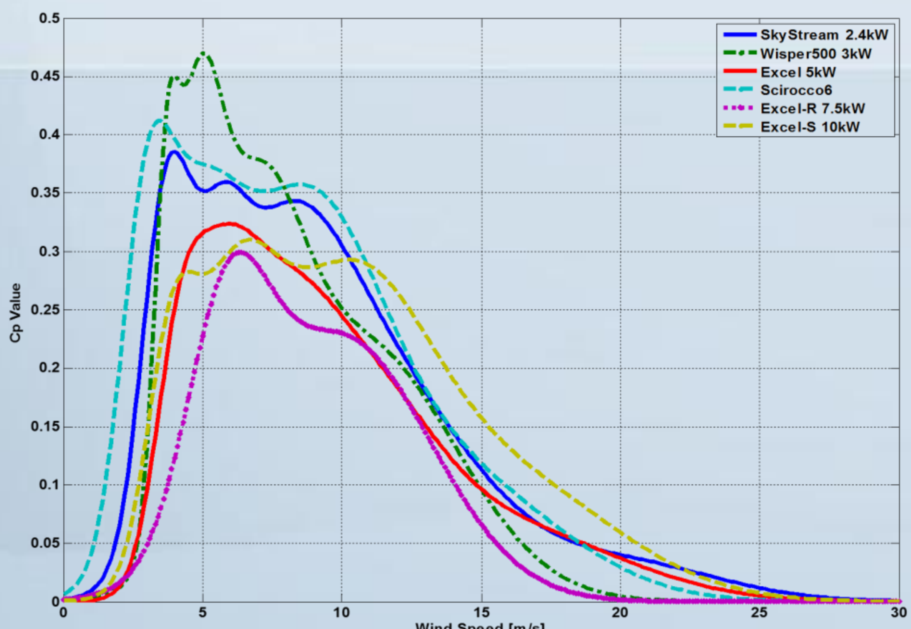
Wind turbine model	Rating Power [KW]	Rotor Diameter [m]	Tower Height [m]	Survival Wind Speed [Km/hr]
Sky Stream	2.4	3.72	13.7 (zone 3)	226.8
Wisper 500	3	4.5	13.7	198
Excel-5	5	6.2	24	216
Scirocco	6	5.6	24	216
Excel-R	7.5	7	24	201
Excel-S	10	7	24	201

❖ Obtain the C_p variation as a function of wind speed

Bergey Excel-S

$$C_p = a_1 e^{-\left(\frac{WS-b_1}{c_1}\right)^2} + \cdots + a_4 e^{-\left(\frac{WS-b_4}{c_4}\right)^2}$$

Parameter	Value	Parameter	Value	Parameter	Value
a_1	0.2	b_1	5.963	c_1	2.218
a_2	0.1555	b_2	3.825	c_2	1.228
a_3	0.2439	b_3	10.06	c_3	4.004
a_4	0.1056	b_4	15.59	c_4	5.769



Wind turbine performance assessment

- Applying the wind speed profile to 6 different wind turbines.

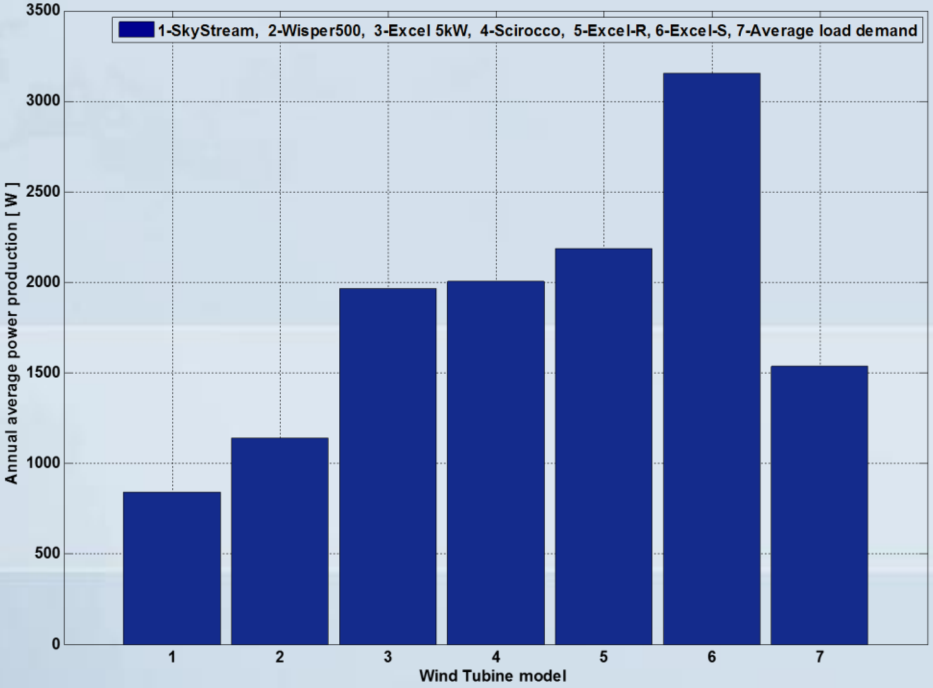
- Different power rating

- The wind speed profile should be corrected based on the required wind turbine tower height.

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^{\alpha}$$

Wind turbine performance assessment, Cont.

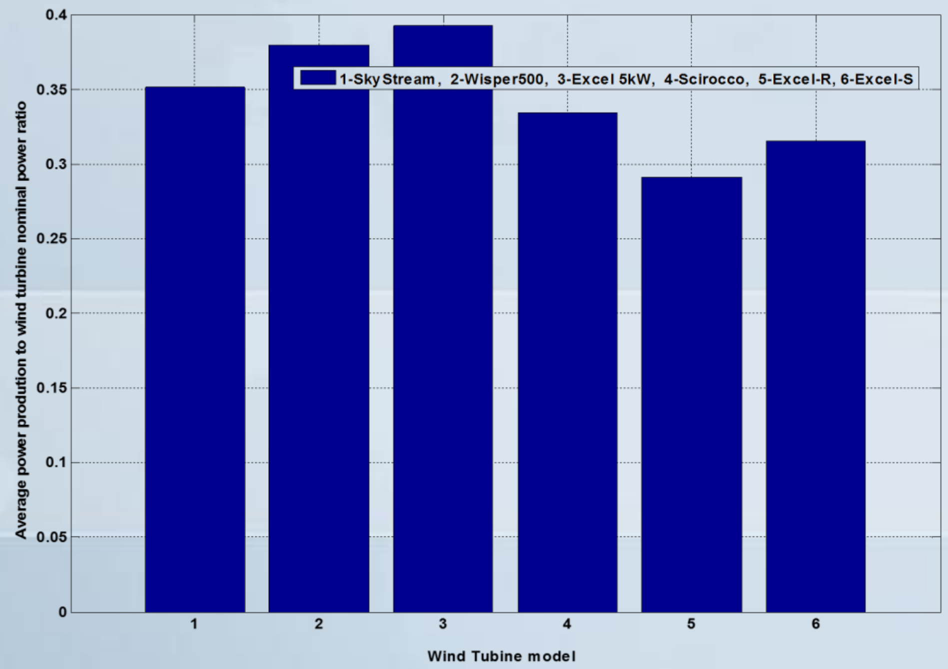
❖ Annual Average output power



- ➢ SkyStream and Wisper 500 cannot provide the required power
- ➢ Excel-S is considered an overdesign
- ✓ Scirocco, Excel-5 and Excel-R able to meet the demand

Wind turbine performance assessment, Cont.

❖ $$Performance\ index = \frac{Average\ Annual\ output\ Power}{Rated\ output\ Power}$$



- ✓ Excel-5 wind turbine has the highest value and it can deliver the required power to the load.
- ➢ SkyStream and Wisper 500.
- ➢ Scirocco, Excel-R and Excel-S

Harvested Energy Index

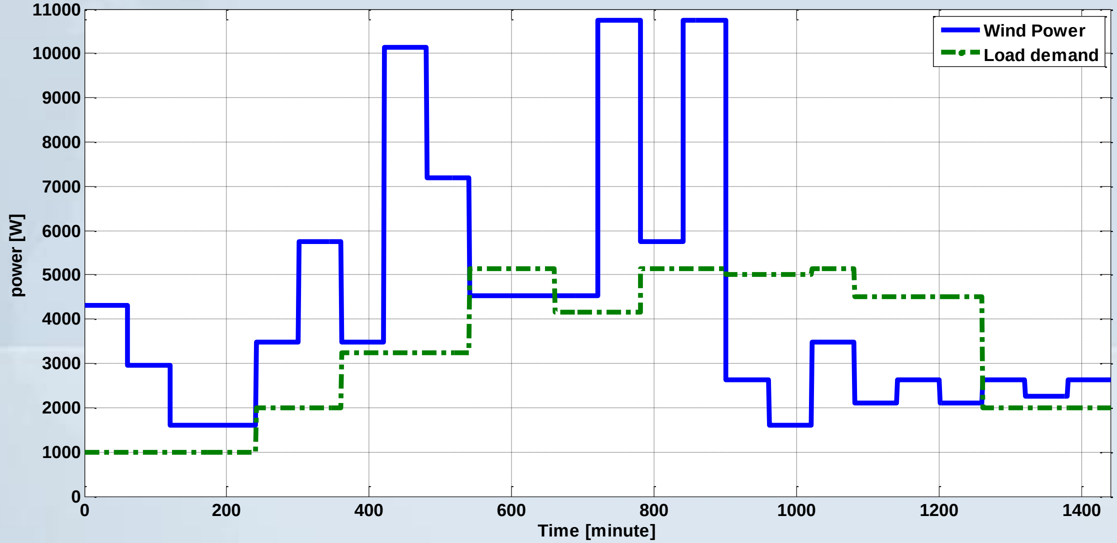
- New criterion for energy storage performance assessment
  - Limited capacity of energy storage systems
  - Large amount of energy in a short time
  - Significant wind speed fluctuation

- Rejected energy
  - Wind turbine control
  - Dump load in isolated applications

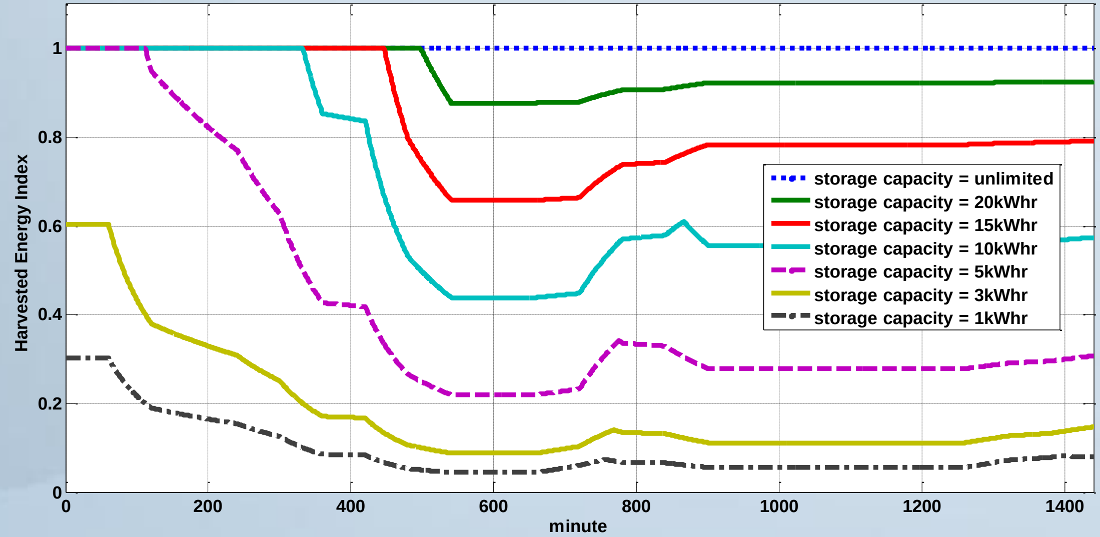
$$HEI = \left(\int_0^{t_s} E_{stored}(t)dt\right) / \left(\int_0^{t_s} E_{excess}(t)dt\right)$$

Case study for storage system sizing

- ❖ Wind power and demand

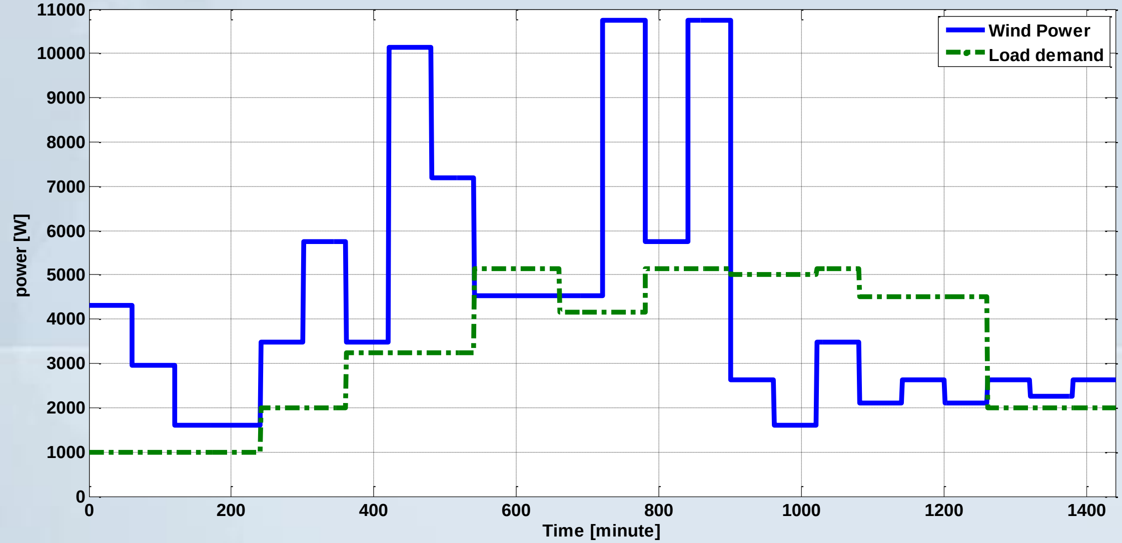


- ➢ HEI for different storage system ratings

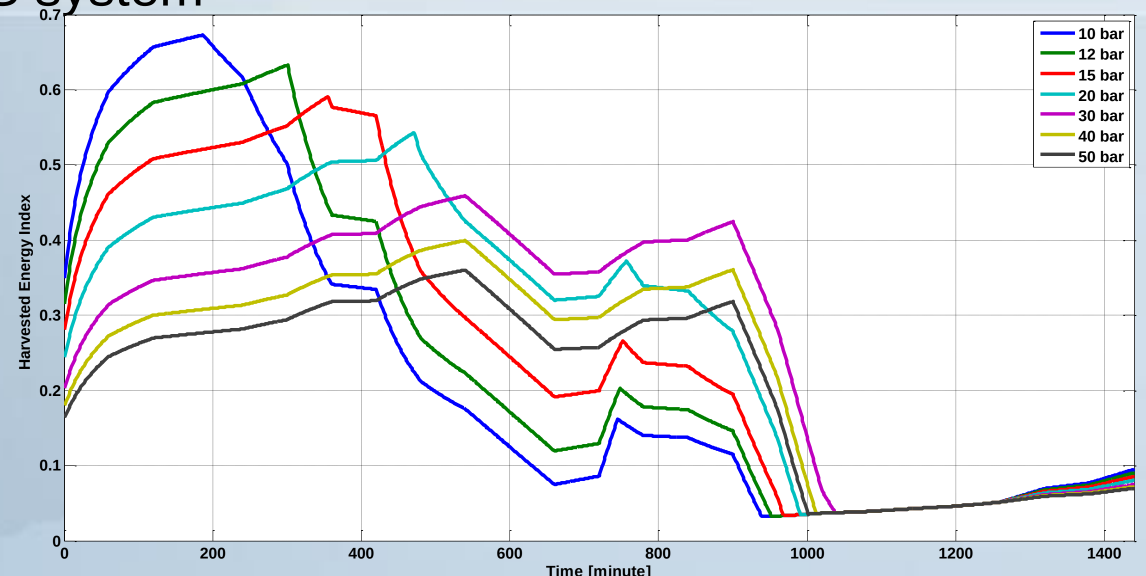


HEI for CAES system

❖ Wind power and demand

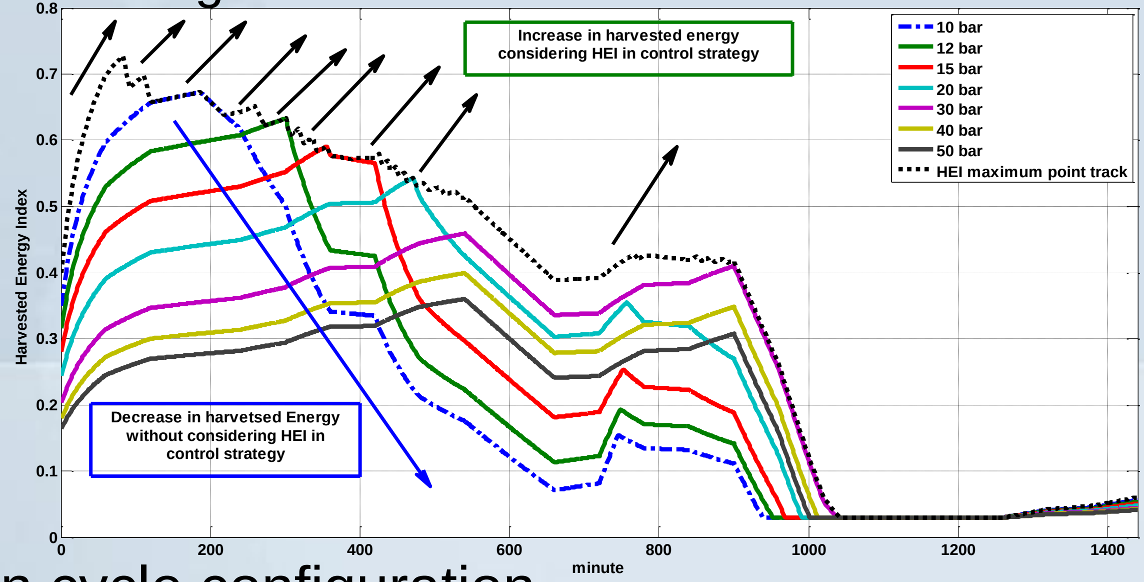


➢ HEI for CAES system

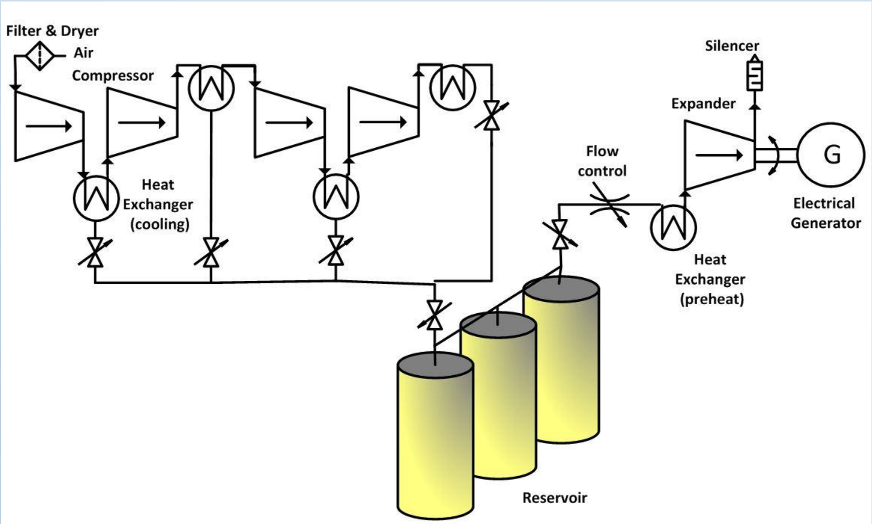


Max. HEI tracking control strategy

❖ Maximum HEI tracking

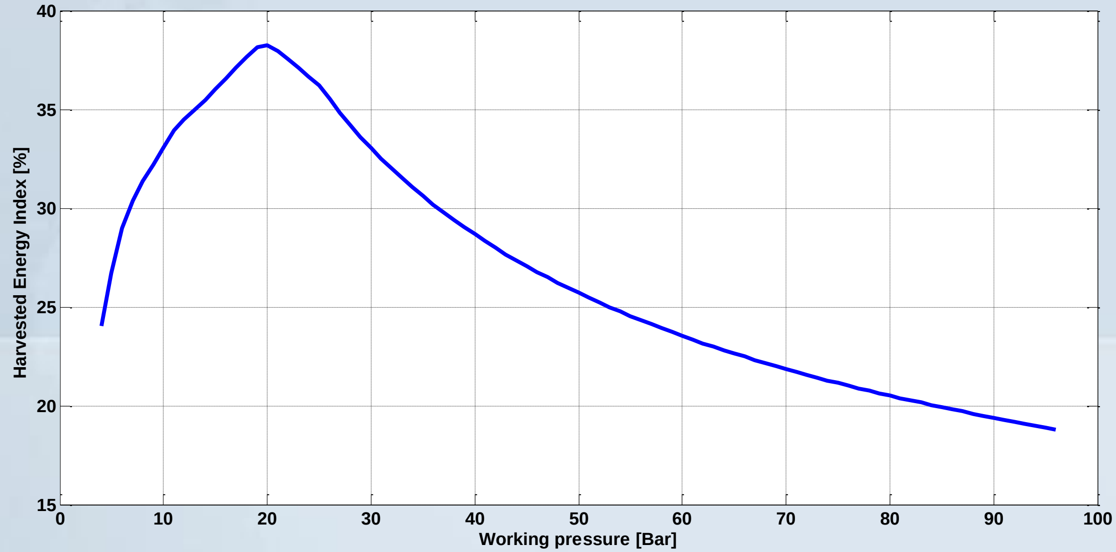


❖ Compression cycle configuration

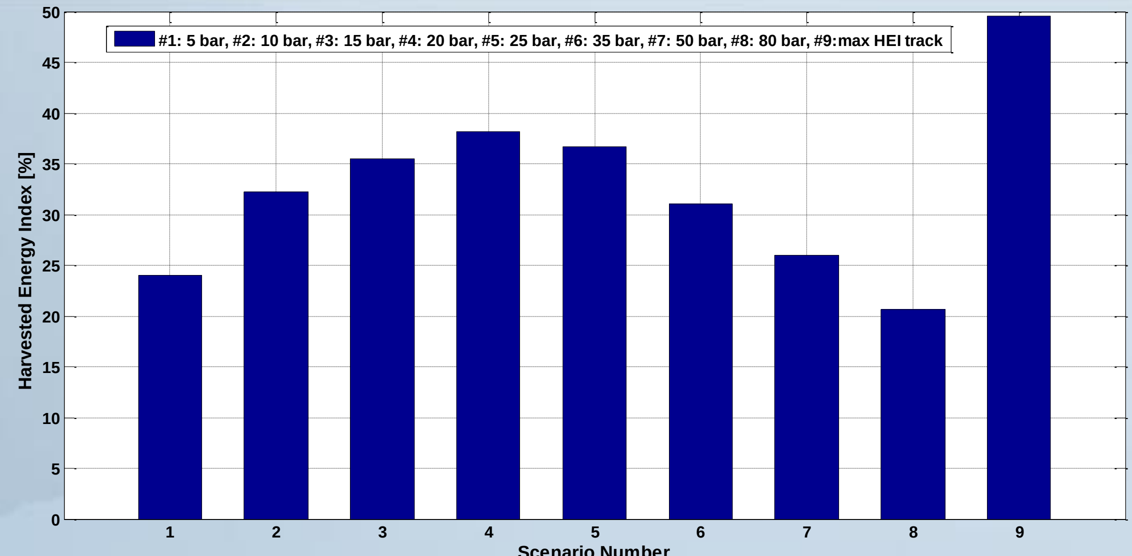


Daily Averaged HEI

❖ Averaged HEI for fixed compression ratios

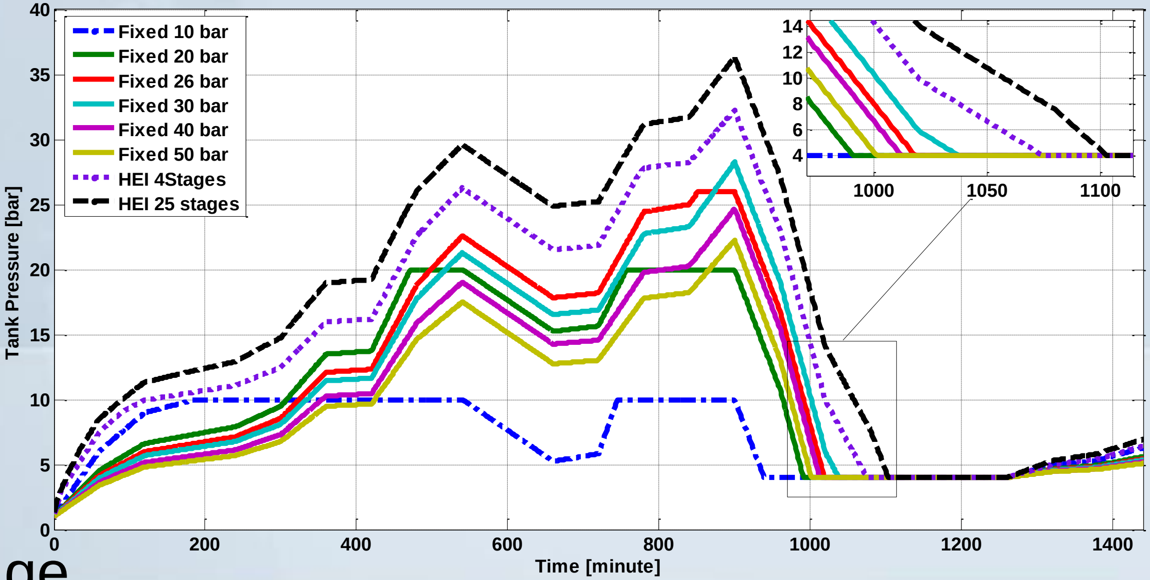


❖ Comparison



Impact of control on total shortage

❖ Tank pressure



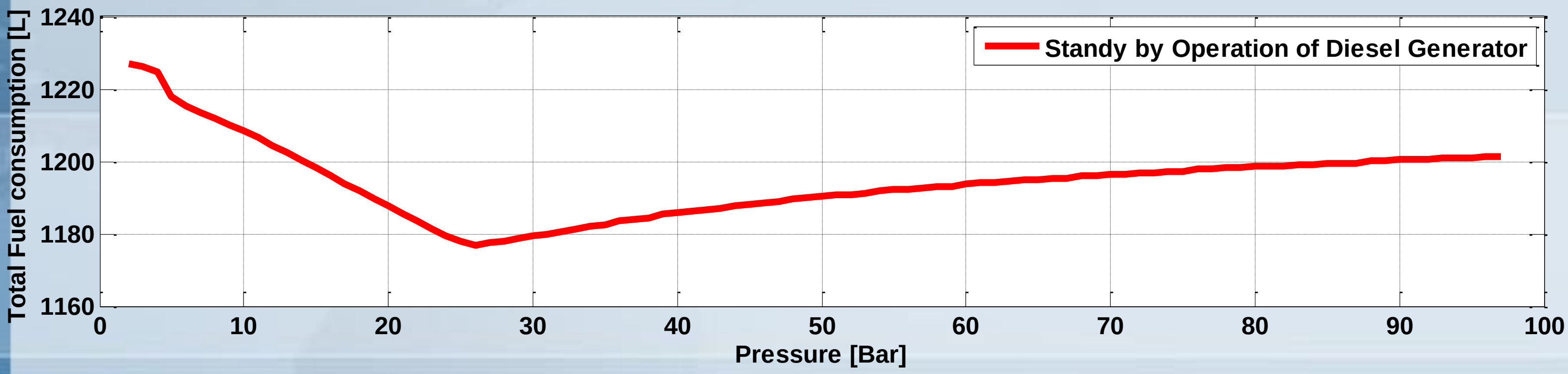
❖ Total shortage

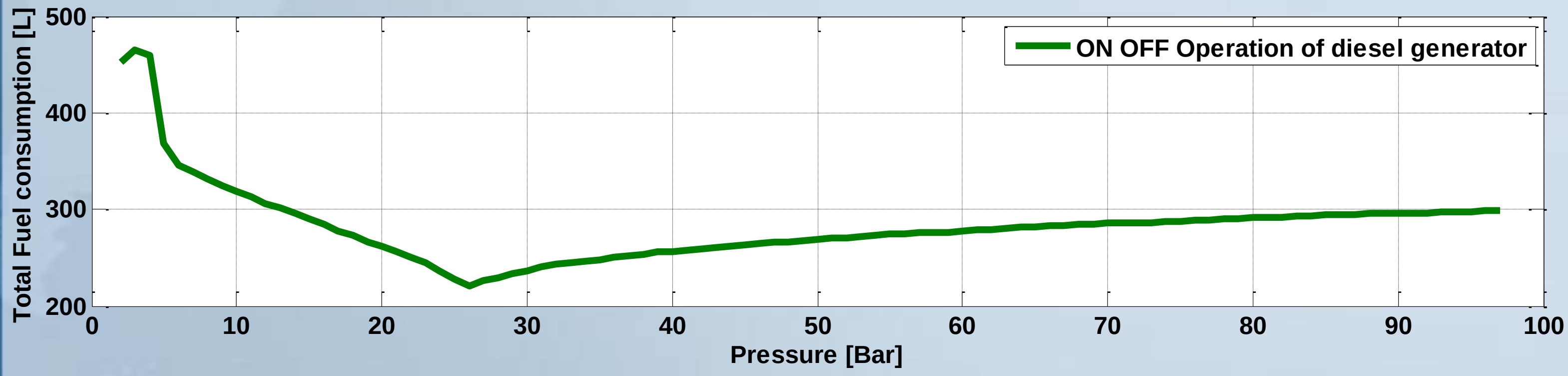
Control method	Fixed 10 bar	Fixed 26 bar	HEI in 25 stages	HEI in 4 stages
Shortage Duration	326 [min]	225 [min]	163 [min]	192 [min]

Diesel Generator Fuel consumption

❖ On-off mode, only on shortage duration

❖ Standby operation





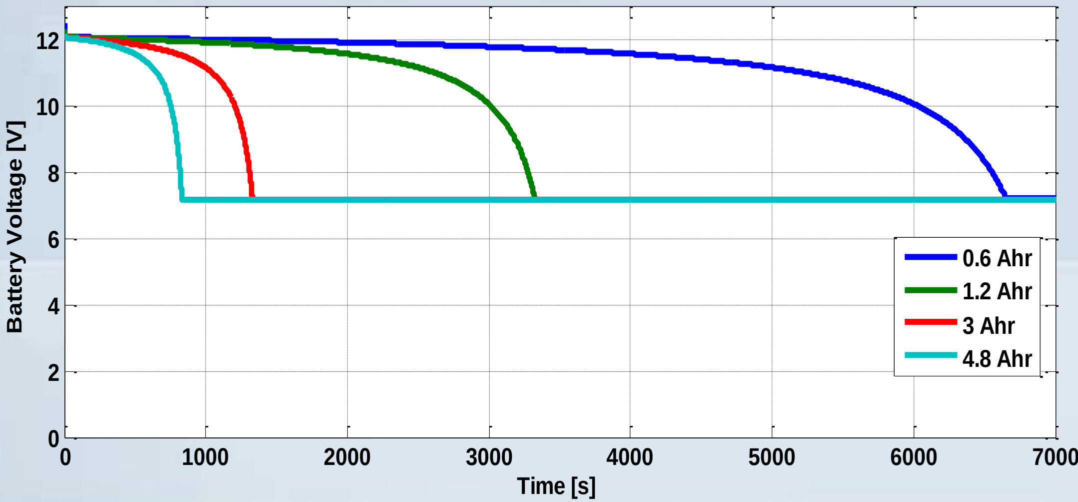
❖ No load fuel consumption

HEI for Battery storage system

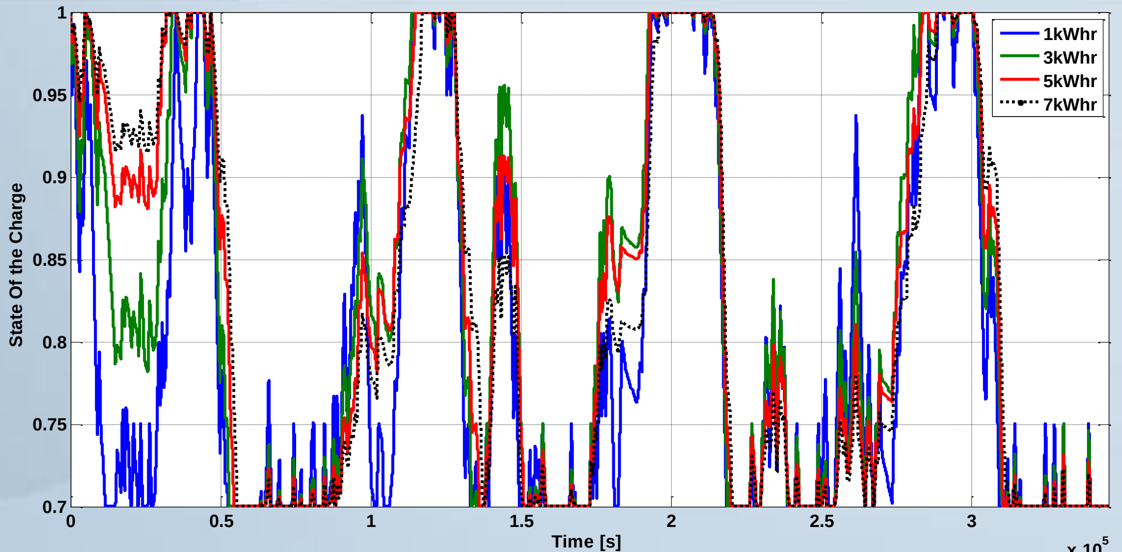
- Battery terminal voltage

$$E = E_0 - K\left(\frac{Q_{rated}}{Q_{rated} - Q_{exchanged}}\right) + Ae^{-BQ_{exchanged}}$$

$$Q_{exchanged} = \int idt$$

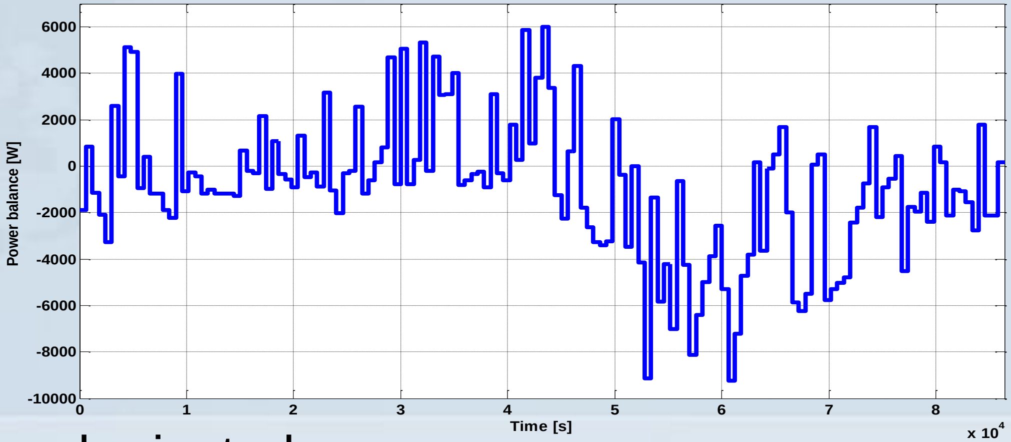


- SOC

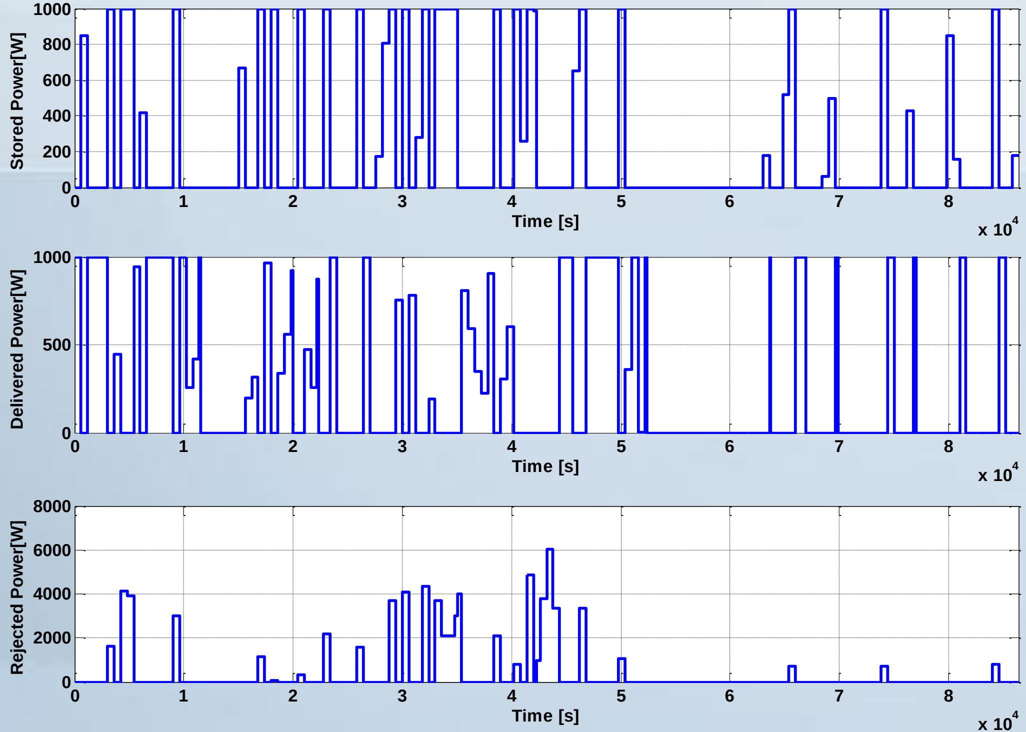


HEI for Battery storage system

❖ Power balance

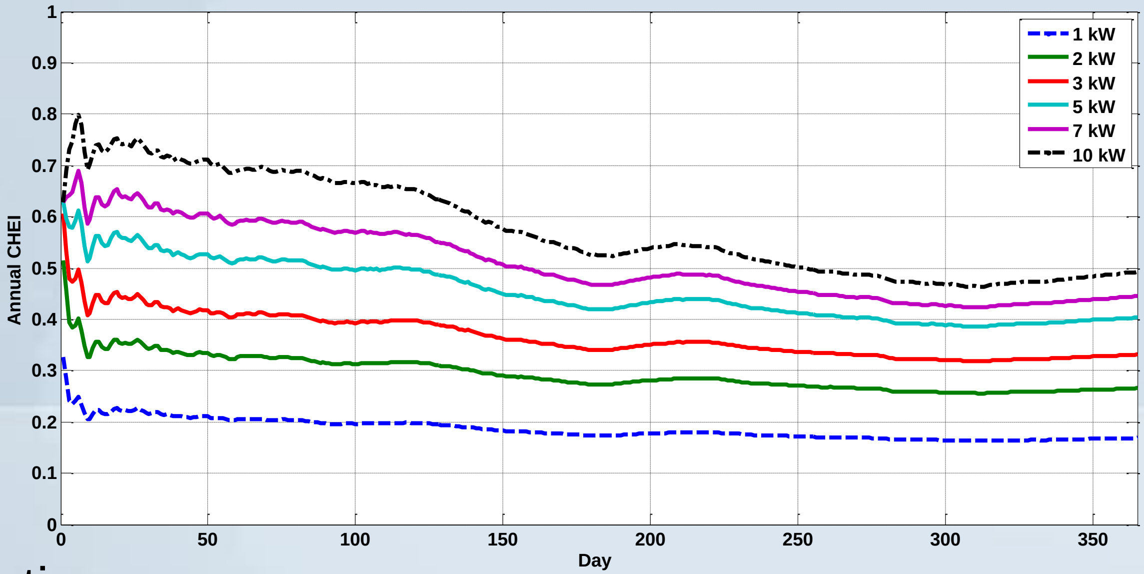


❖ Stored, Delivered and rejected power

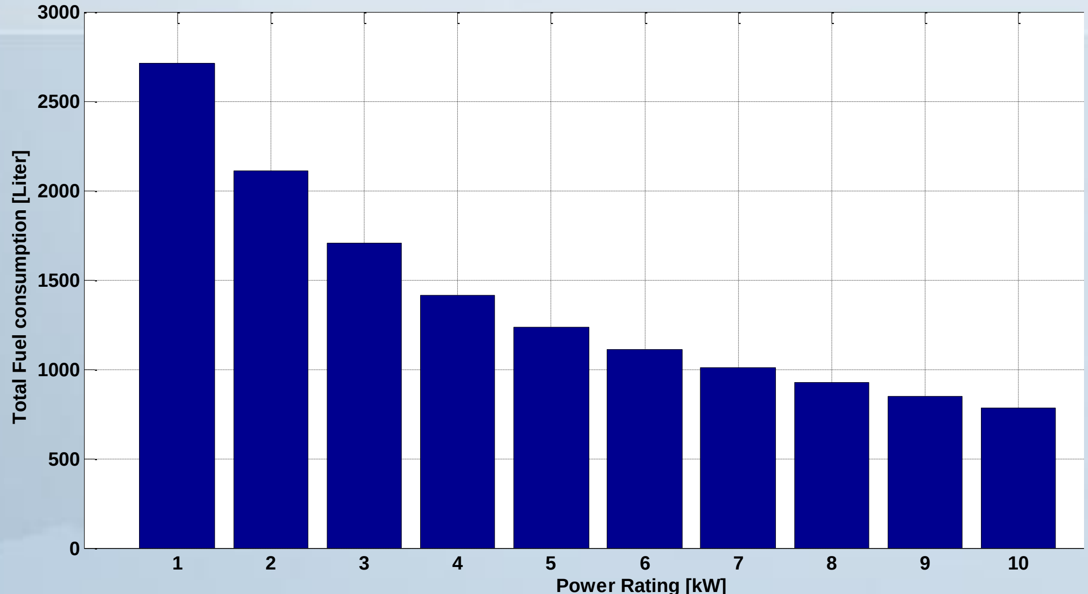


Annual HEI for BES system

- ❖ Annual HEI

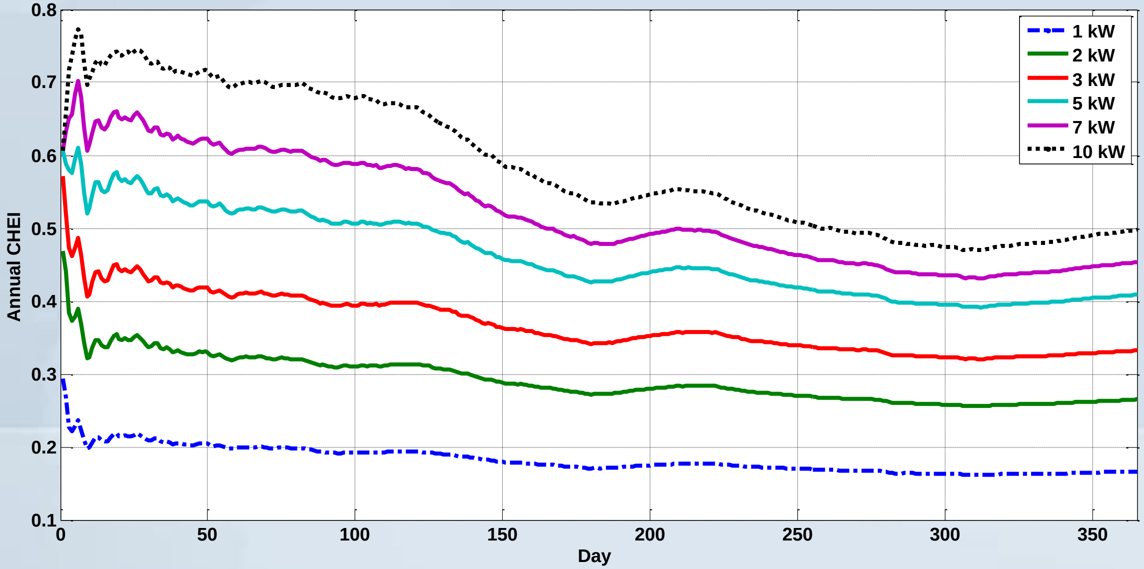


- ❖ Fuel consumption

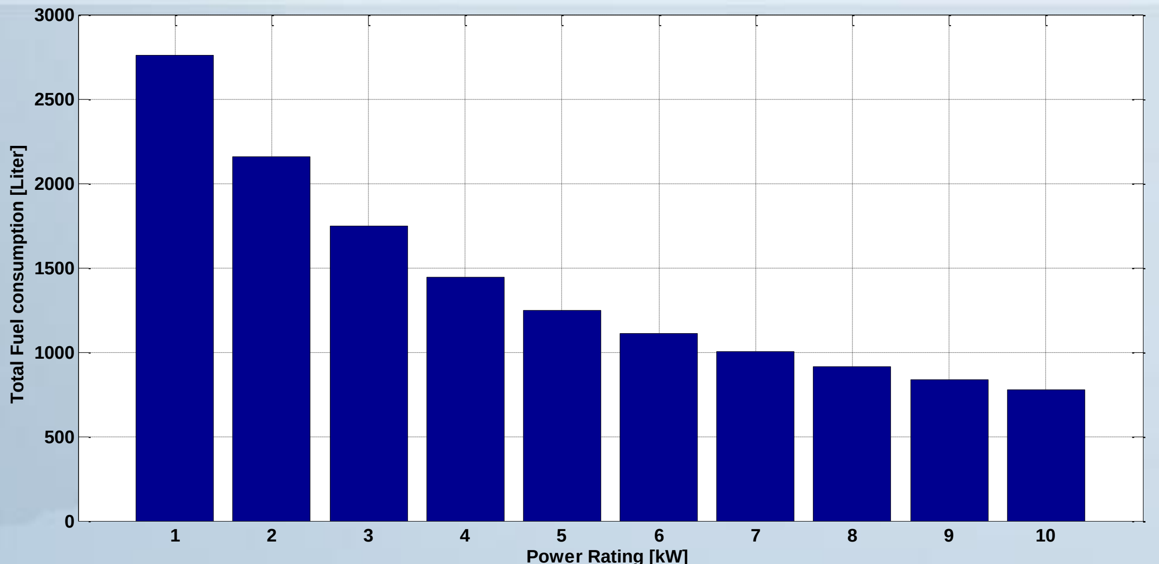


Pumped Hydro Energy Storage

❖ Annual HEI

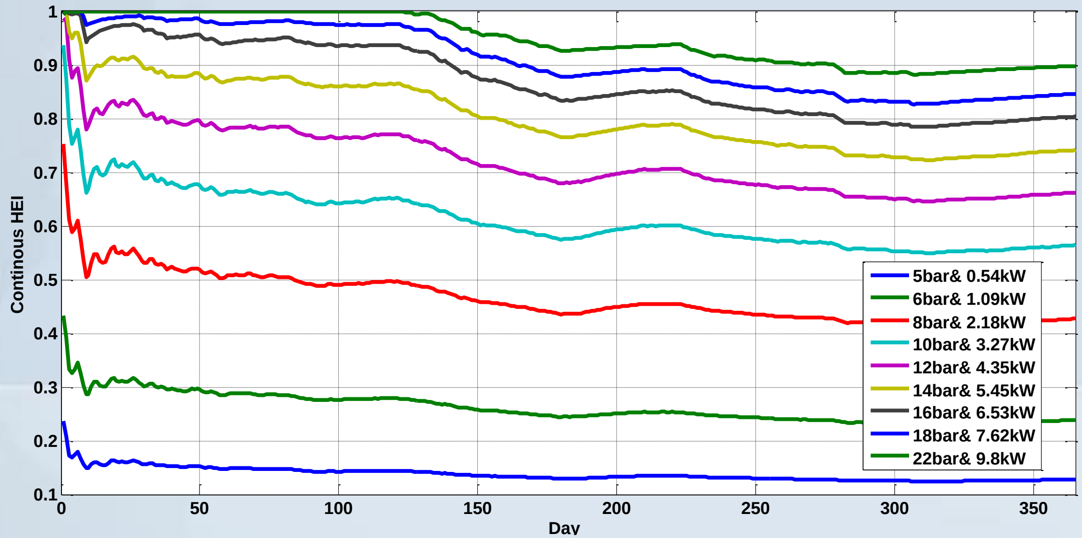


❖ Fuel consumption

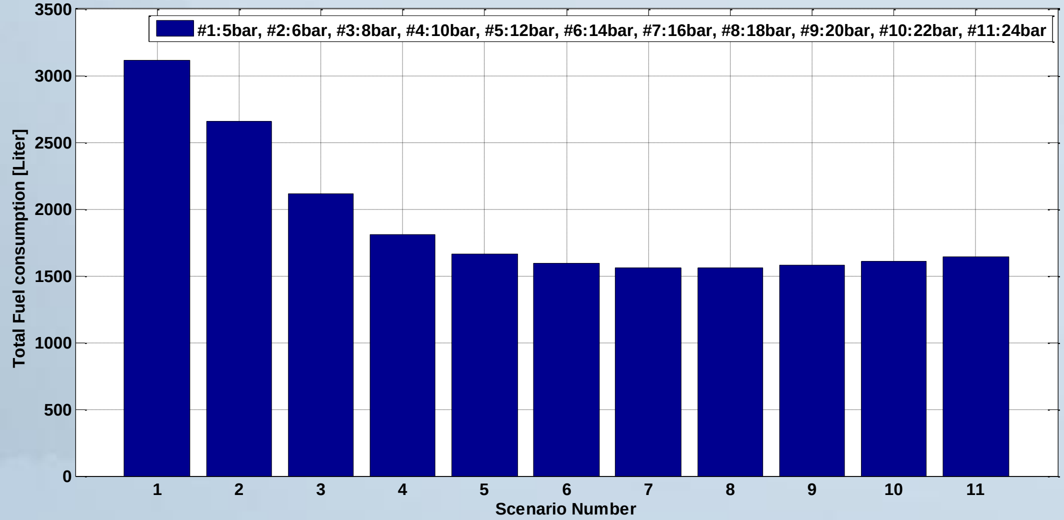


CAES system

- Annual HEI

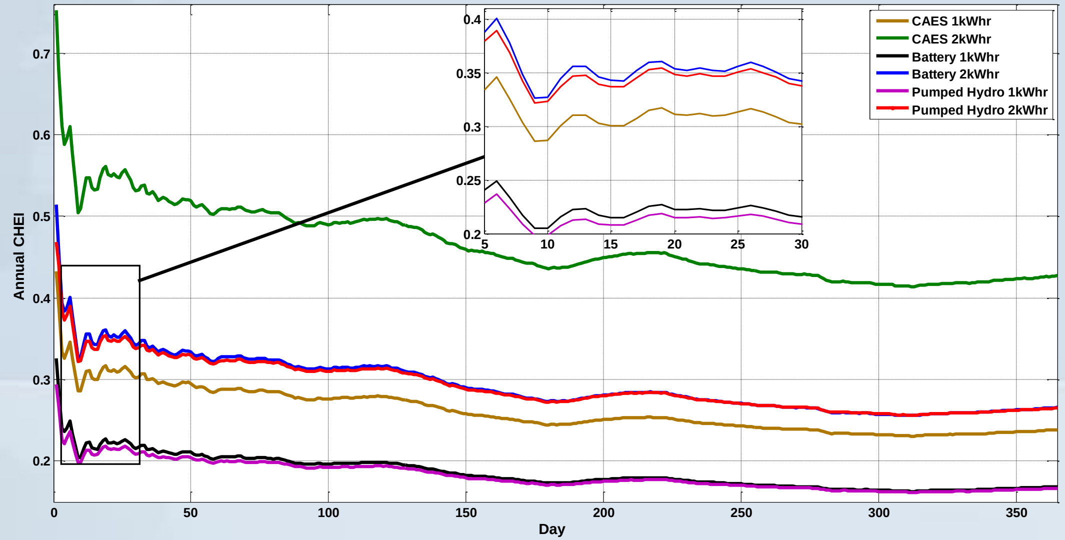


- Fuel consumption

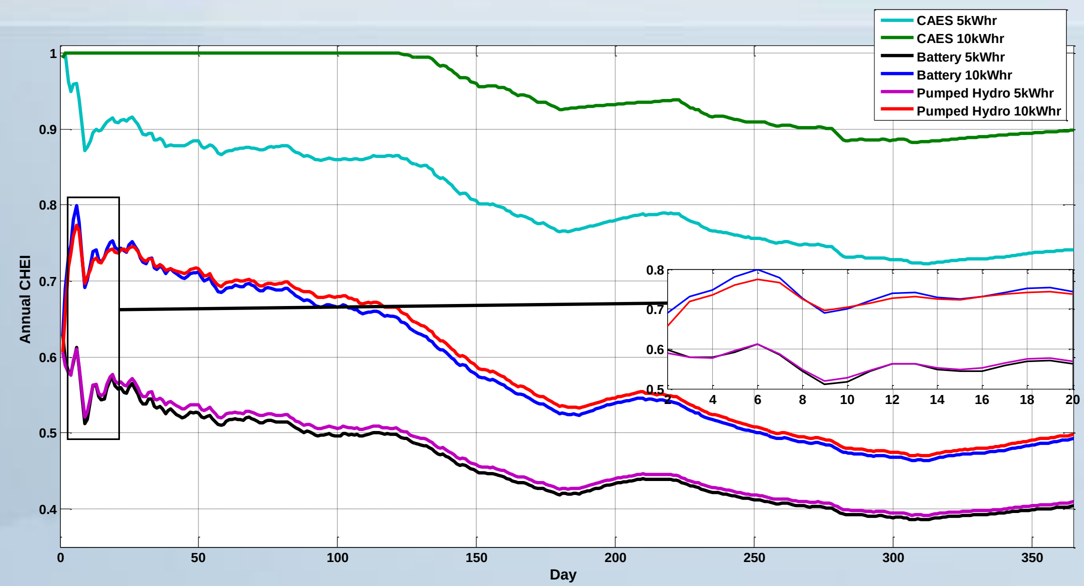


Annual HEI comparison

- ❖ 1 kWh & 2 kWh

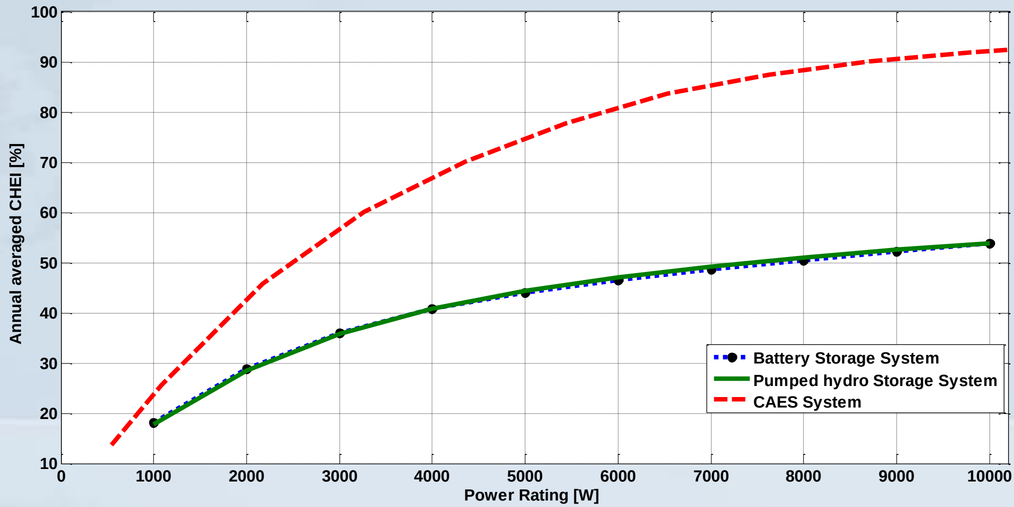


- ❖ 5 kWh & 10 kWh

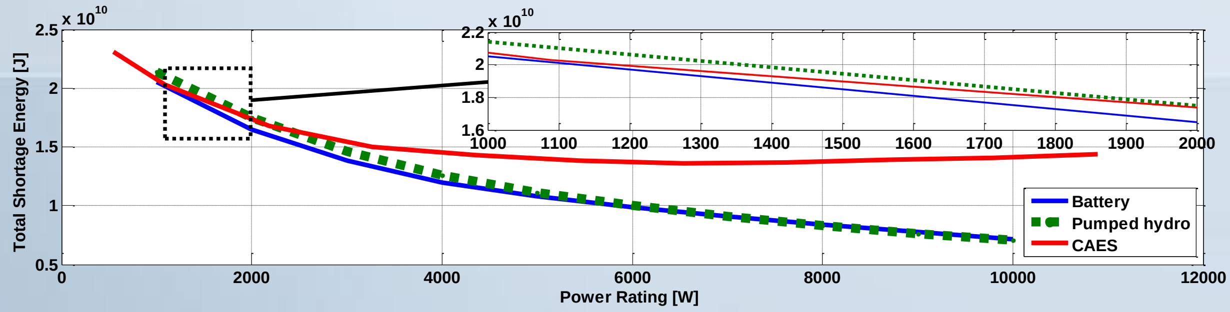


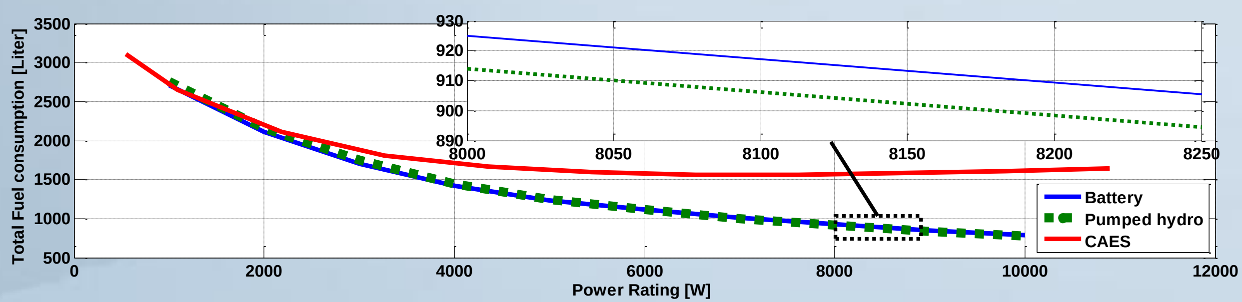
Annual HEI comparison Cont.

❖ Annual Average



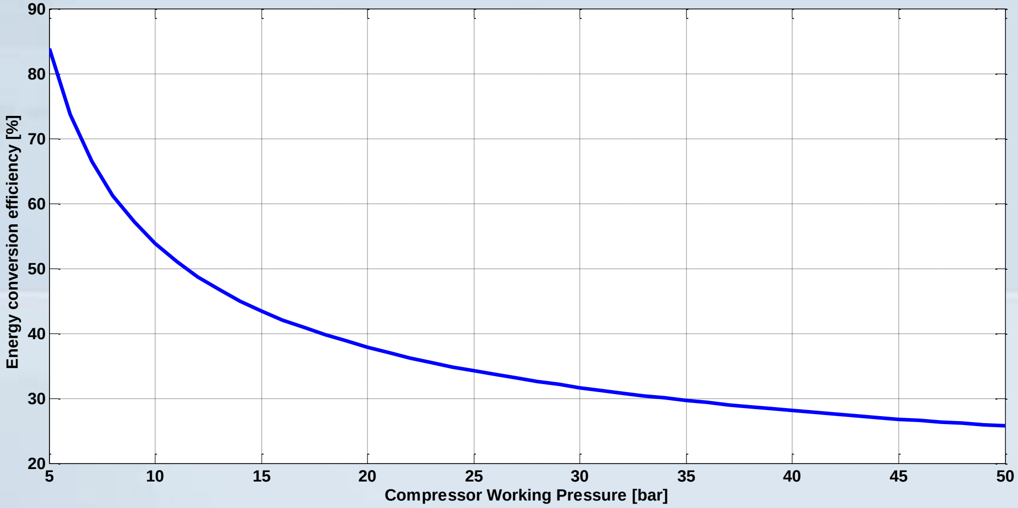
❖ Annual Shortage



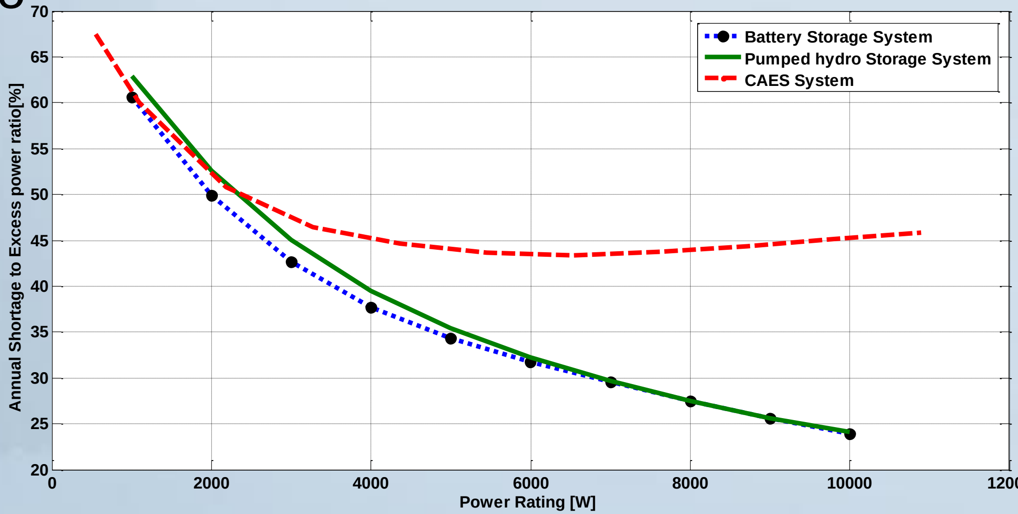


Annual HEI comparison Cont.

❖ Low efficient system with single stage, high pressure and no heat exchanger



❖ Annual shortage to Excess power



Summary of contributions

- A CAES system was developed for isolated applications.
- Mathematical modelling of CAES system
- Simplified air motor and flow rate control valve validation through experiment
- Wind speed profile regeneration using Combined direct sampling method and Monte Carlo simulation.

Summary of contributions

- ❖ Hybrid energy system optimization and component sizing
- ❖ Development of a new criterion based on HEI.
- ❖ Performance evaluation of different energy storage systems
- ❖ Impact of control strategy and storage rating on total fuel consumption

Research outcomes

- H.SedighNejad, T.Iqbal and J.Quaicoe,” *Compressed Air Energy Storage System Control and Performance Assessment Using Energy Harvested Index*”, Electronics Special Issue on Renewable Energy Systems, 2014, 3, 1-21.

- H.SedighNejad, T.Iqbal and J.Quaicoe, “*Effect of the sizing of compressed air storage system on overall performance of Hybrid systems*”, poster presentation at CanWEA’s 26th Annual Conference and Exhibition, November 1-3, 2010, Montreal, Quebec.

- Hanif Sedighnejad, T. Iqbal, J. Quaicoe,” *Design Considerations for Compressed Air Energy Storage Systems*”, 2010, PKP Open Conference Systems, presented by IEEE Newfoundland and Labrador Section.

Research outcomes cont.

- H.SedighNejad, T.Iqbal and J.Quaicoe, "*Performance evaluation of a hybrid wind-diesel-compressed air energy storage system*", 24th Canadian Conference on Electrical and Computer Engineering (CCECE), 8-11 May 2011, Niagara Falls, ON Page(s): 000270 – 000273.
- H.SedighNejad, T.Iqbal and J.Quaicoe, "*Design and dynamic modeling of a micro compressed air energy storage system*", poster presentation at CanWEA's 27th Annual Conference and Exhibition, October 3-6, 2011, Vancouver, BC.
- H.SedighNejad, T.Iqbal and J.Quaicoe, "*A compressed air storage system Design and Steady-State Performance Analysis of CAES*", The Twentieth Annual Newfoundland Electrical and Computer Engineering Conference (NECEC), Nov. 1st, 2011.

Research outcomes cont.

- H.SedighNejad, and T.Iqbal, "*Simplified dynamic model for vane type air motor*", The 21th Annual Newfoundland Electrical and Computer Engineering Conference (NECEC), Nov. 8^{th}, 2012.

Suggested Future Work

- Application of heat exchanger to improve the efficiency

- Dynamic control of the CAES system in conjunction with another energy source,

- Evaluation of the system with capability of working in series/parallel configuration and its impact on round trip efficiencies and system power ratings

MEMORIAL UNIVERSITY

Thanks for your attention