Hafod y Rhedwydd micro-hydro system – turbine and alternator choices.

Roger Moss, May 2019

Contents

Abstraction system and penstock

Hafod y Rhedwydd is an off-grid cottage on the southern edge of Snowdonia (LL24 0RF). Planning permission and preliminary FIT accreditation have now been obtained for the construction of a 9 kW micro-hydro system to provide electricity to the cottage.

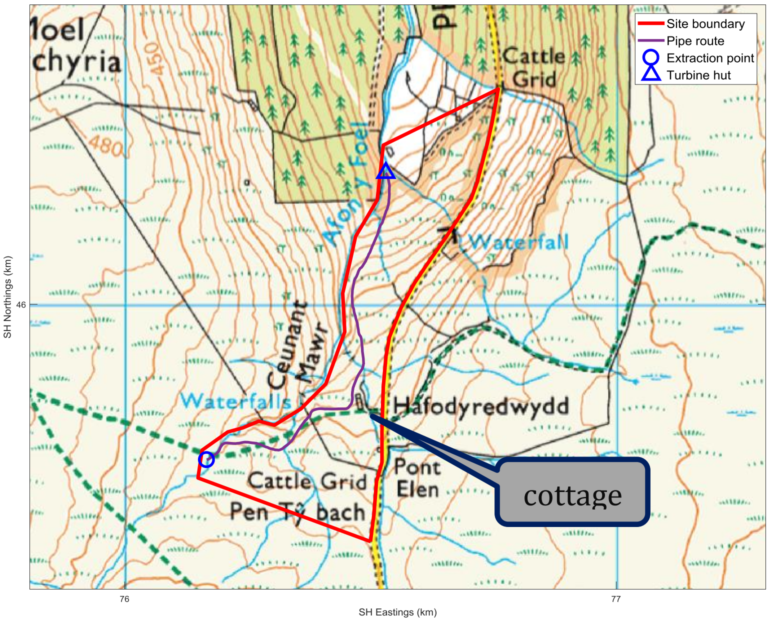


Figure 1. Map showing extraction point, penstock route and turbine hut. The head is 150 m. Map scale 1: 10000 (grid squares are 1 km wide). OS map is © Crown Copyright, reproduced by permission of Ordnance Survey.

Water will be taken from Afon y Foel, the small stream running down behind the house (Fig. 2). The head is 150 m.

Figure 2. (a) Hafod y Rhedwydd, (b) Stream at the extraction point (stick with 1 m tape markers to show scale).

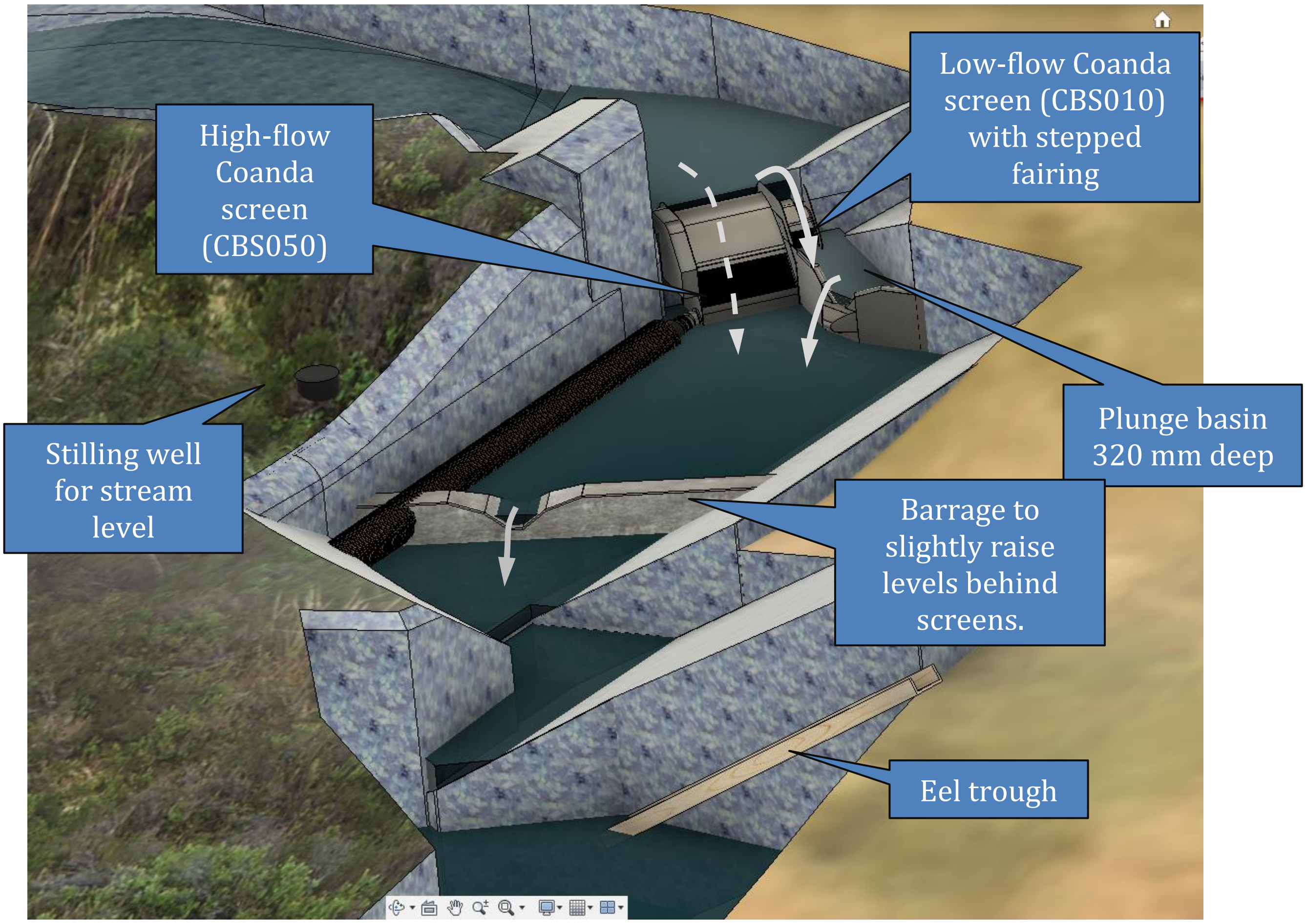


Figure 3. Abstraction system. Fish can progress up and downstream in three stages (black arrows). Water level increment 25 cm for each (shown for stream flow of 4 litres/sec, Q95) – jump from water up to weir crest is slightly less. At higher stream levels, water starts to flow over the high flow screen (dashed arrow). The main screen is generously sized relative to the penstock.

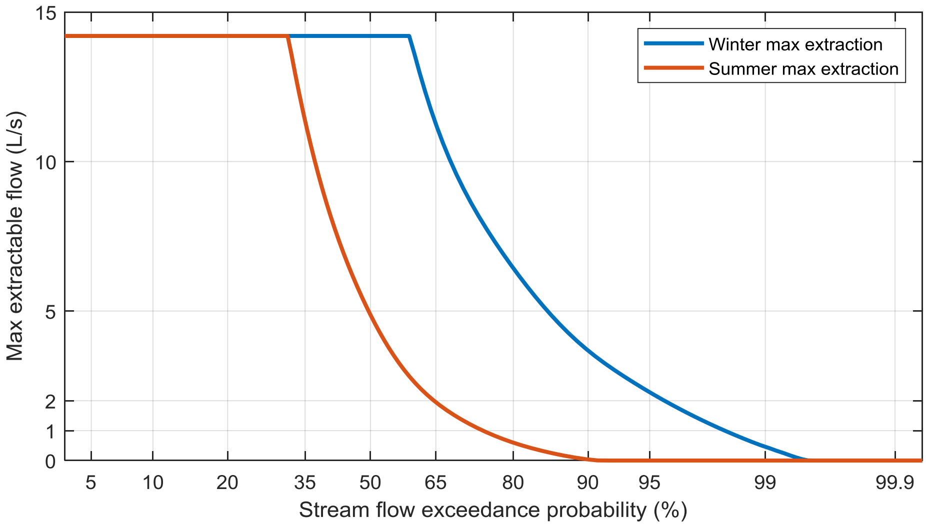


Figure 4. Extraction limits as per the Abstraction Licence (no HEP extraction beyond Q95), screen flow rates and LowFlows simulation (split into October-March versus April-September).

Figure 5. The penstock has a tee-off to the house before continuing for another 475m towards the bottom of the valley.

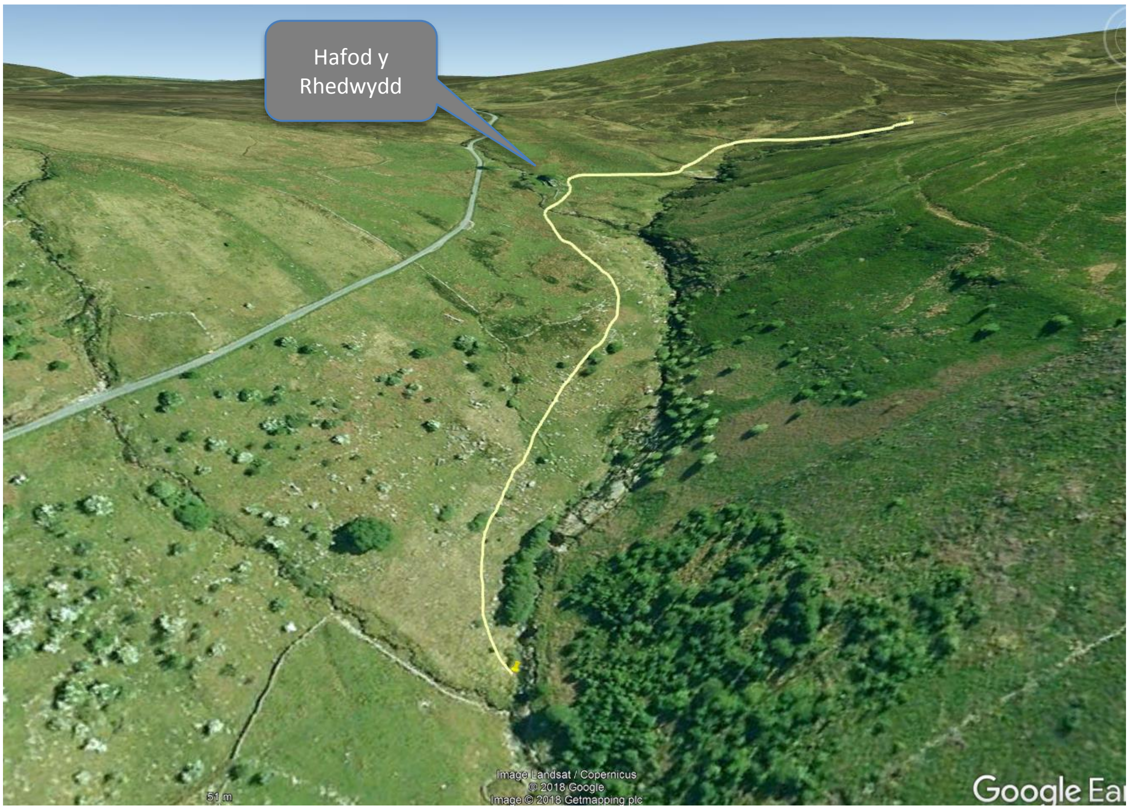


Figure 6. Penstock route below the cottage.

The penstock will be made from HDPE pipe (first 40 m to settling tank is 160 mm OD, then 615 m of 10 bar 110 mm, finally 200 m of 16 bar 110 mm).

Turbine and alternator choices

In wet weather the cottage will use up to 9 kW to run electric radiators and immersion heater. In dry weather however the amount of water that may be extracted from the stream is severely limited (typically no extraction at all for 3 weeks each summer and <1 litre/sec for a further 4 weeks, when it may only generate 100 – 1000 Watts). The electricity in this peak holiday season is particularly valuable for running a UV water steriliser, fridge, lighting and satellite broadband dish, so good system efficiency is important.

To provide reasonable efficiency over a 100:1 variation in power, the system will use a large and a small turbine:

- wet weather turbine & alternator, up to 9-10 kW output
- dry weather turbine and alternator, up to perhaps 1-2 kW output

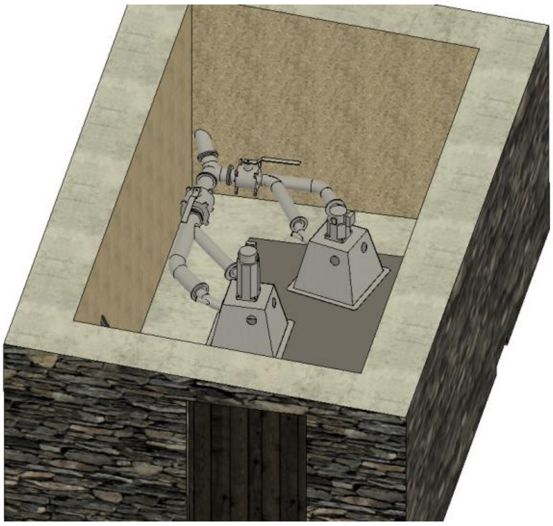


Figure 7. Turbine hut layout. To ensure reliable operation over at least a 10:1 flow range, each turbine will have a main spear valve plus a much smaller one for low flow rates.

Figure 8. Turbine hut location.

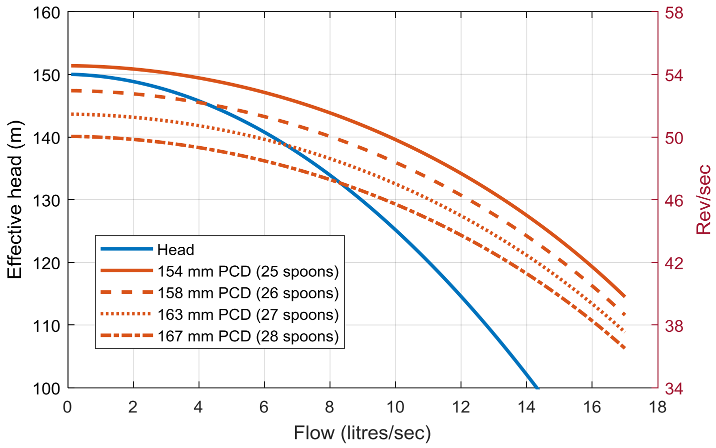


Figure 9. Head loss curve and turbine speed (Hz for 2-pole alternator) at $V_{runner}/V_{jet} = 0.49$ for Hartvigsen 75% Orange Spoon runners. These runners would satisfy the electricity meter specification of 50 Hz ±10% for up to 11 litre/sec without deviating from the 49% optimum efficiency point.

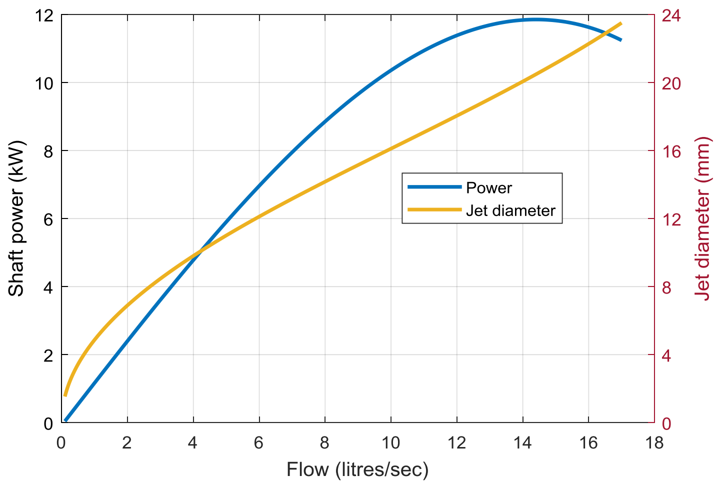


Figure 10. Nominal turbine shaft power assuming 85% turbine efficiency plus 80 W windage loss. Jet diameter is for a single jet.

Hartvigsen Turgo runners:

- “blue spoon” up to 14 mm jet (dry weather turbine)
- “75% scale orange spoon” up to 21 mm jet (wet weather turbine)

The turbine control system will adjust the spear valves to vary the extraction rate in response to power required and stream level (measured just below the screens); the house control system will disconnect loads above the generation capacity based on stream level. A small settling and de-aeration tank about 40m from the screens will contain a second level sensor to warn of any obstruction to flow due to screen blockage.

The initial concept was for Turgo runners (Hartvigsen Hydro) driving 6-pole MOOG alternators at about 4-5000 rpm. At this stage MOOG appeared to be the only manufacturer of high efficiency (permanent magnet) high voltage alternators. The output would be rectified before transmission to the cottage; the cottage system (Fig. 11) would resemble a

PV installation, with all power produced by inverters. I am however now wondering whether it would be better to use a 2-pole, 50 Hz alternator, at least for the main turbine, so that the inverter does not need to supply the heating loads (Figure 12).

Turgo runners seemed the best choice because at low flows (e.g. 0.3 L/s, jet diameter 2.6 mm) a Pelton runner might need a very sharp splitter edge and accurate alignment to split the jet. At high flow rates, a Turgo could operate with a single 18 mm jet whereas a Pelton turbine would need multiple jets or large buckets, perhaps 60 mm wide. (I actually have a 250 mm PCD Pelton wheel that would give 2030 rpm; in principle this could directly drive a MOOG GES018 v3 to give 9.6 kW; not sure what voltage this would give).

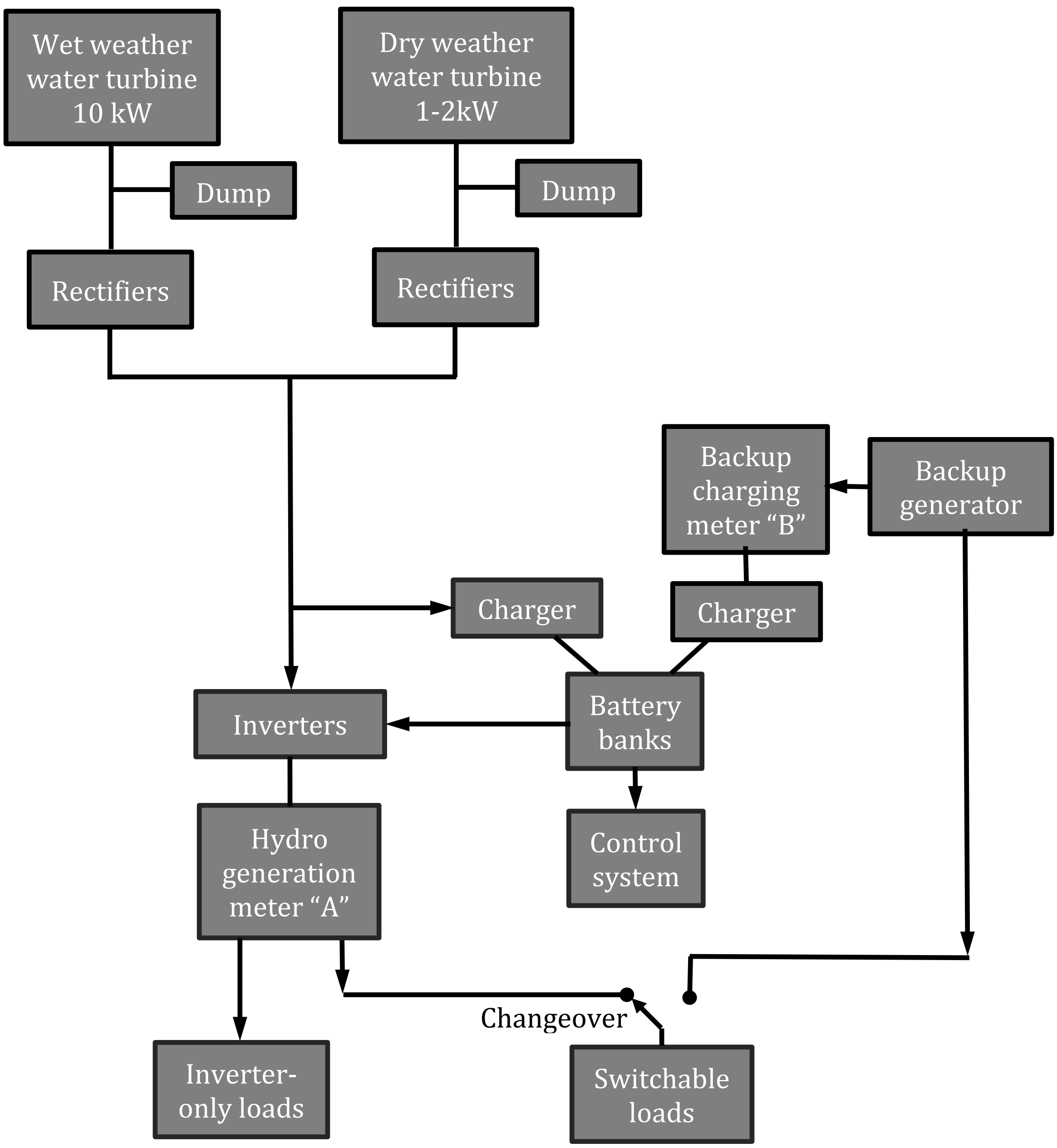


Figure 11. ROOFIT schematic (assuming generation at 150-200 Hz using 6-pole MOOG alternators).

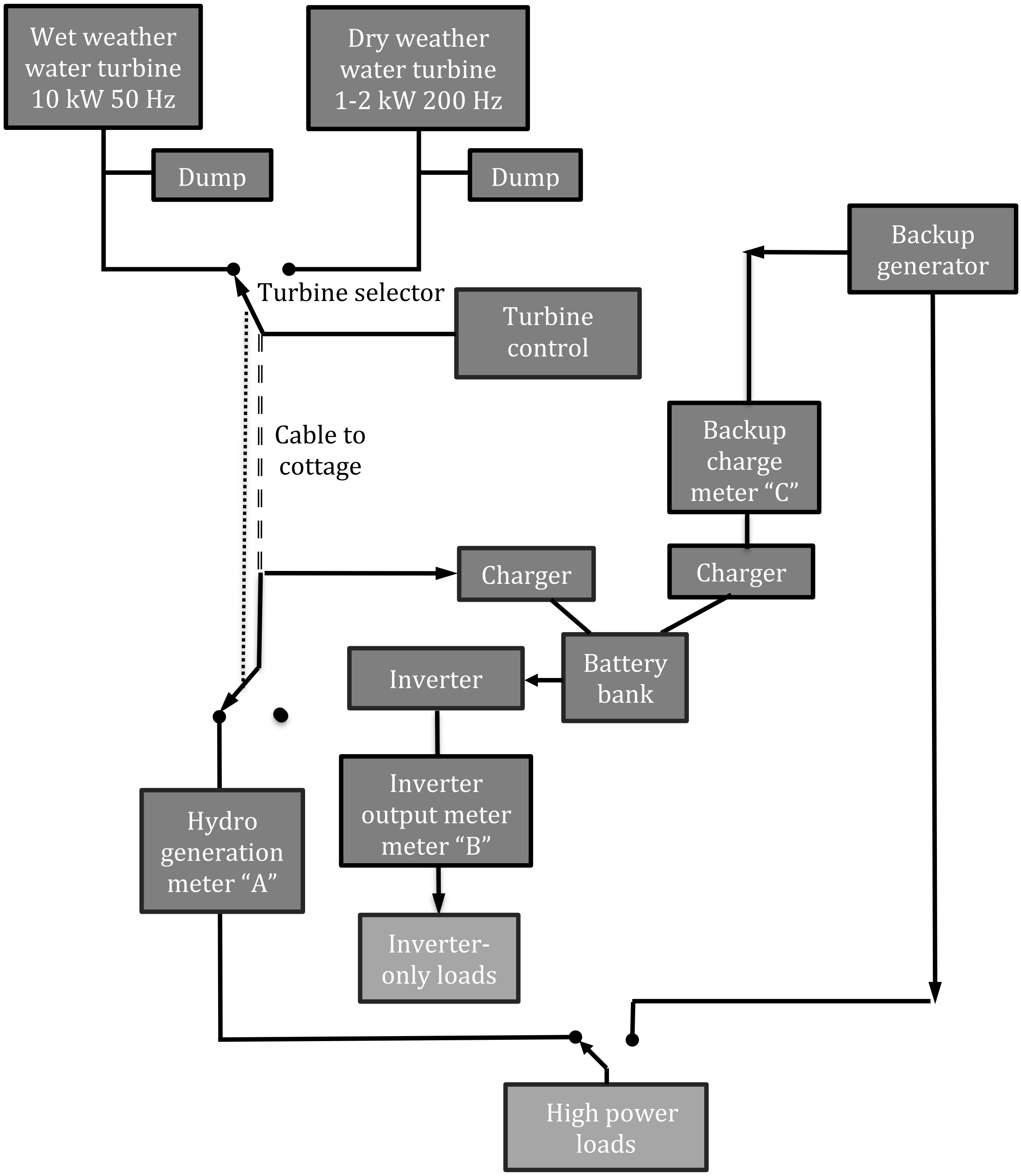


Figure 12. Possible schematic diagram using a 50 Hz wet weather alternator to drive heavy loads directly. Both alternators would generate 240 V (star) 3-phase. (I imagine this would still be acceptable in terms of ROO-FIT).

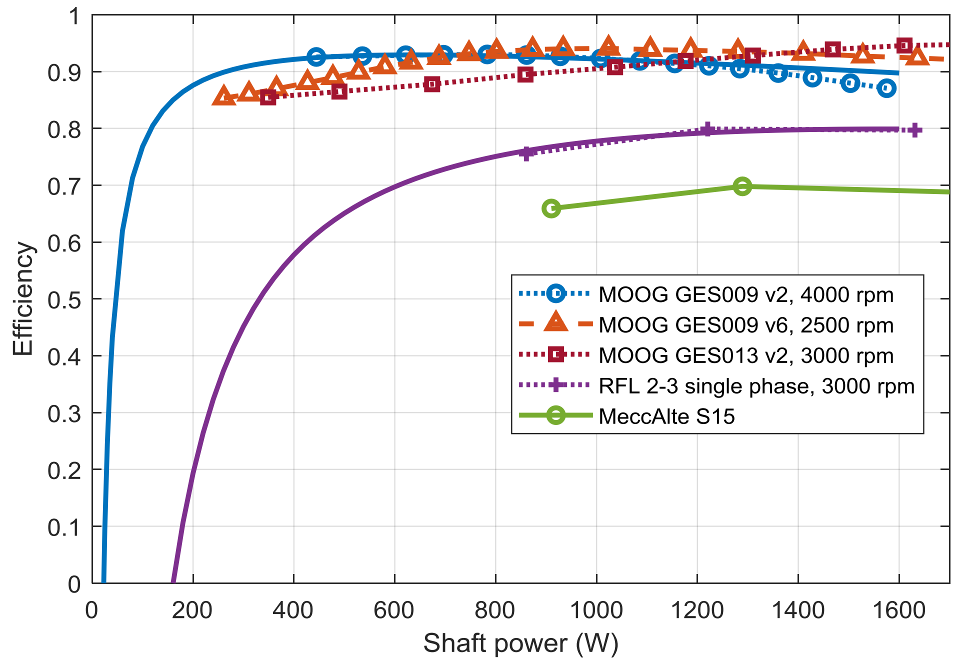


Figure 13. Probable small alternator efficiencies (fitting $\eta = 1 - \dfrac{a + bP_{shaft}^2}{P_{shaft}}$ to model windage and copper losses) for dry weather use. The extrapolated curves are unlikely to be very accurate. See Appendix Table 2 for maximum MOOG power with standard cooling.

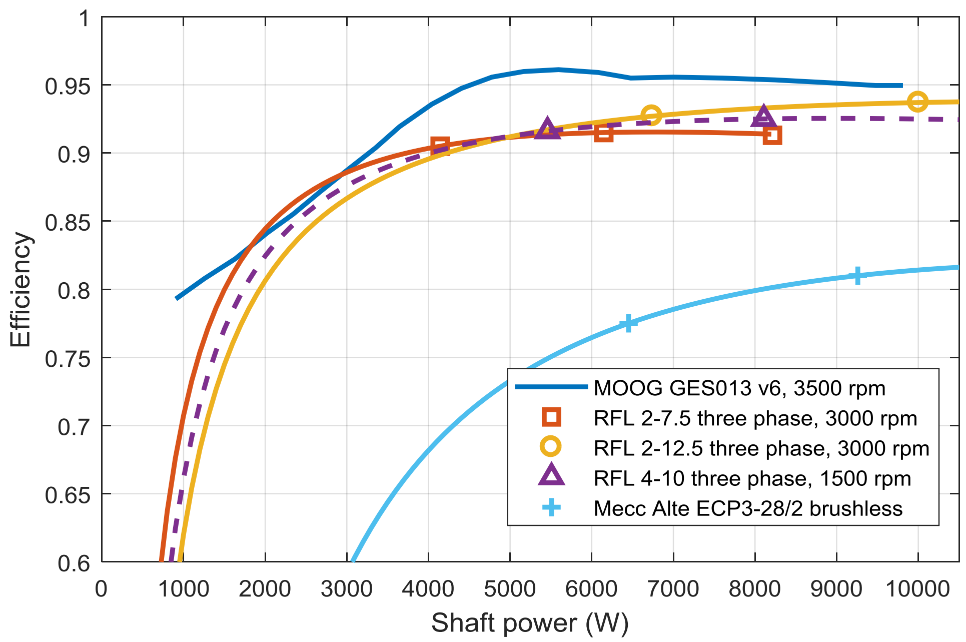


Figure 15. Probable large alternator efficiencies (wet weather); MOOG is not 50 Hz. A larger MOOG alternator (GES013-v8, GES018-v2 or v3) would be less reliant on cooling; efficiency and voltage curves not yet available.

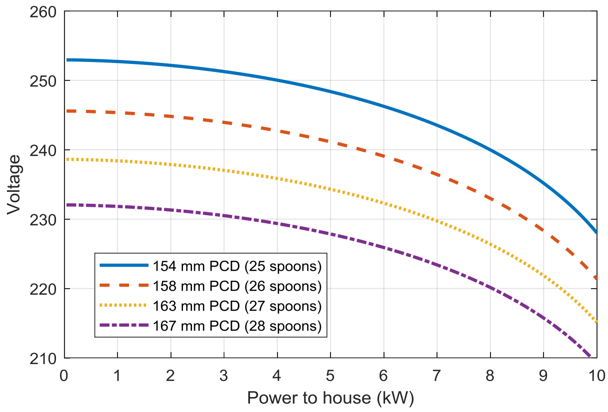


Figure 16. RFL alternator voltages, including penstock head loss and transmission voltage drop (4-core 10 mm^2 cable) if operating at constant V_{runner}/V_{jet} . This assumes no-load 400 V phase-phase at 50 Hz; the alternator voltage-power curve is from their 4-pole data.

Conclusion

- Dry weather turbine: Turgo runner (37-off HH "blue spoon" to give 130 mm PCD, 3930 rpm) driving the MOOG GES009-v2 alternator (or possibly GES009-v4 if the output voltage is suitable). For comparison, the GES009 v6 and GES013 v2 would run at 2100 rpm if generating 240 V, needing a much larger turbine or a belt drive; the increased power from these could however usefully complement the drop in efficiency of the main alternator when powers fall to around 1500 W.

- Wet weather turbine: Turgo runner (26-off HH "75% Orange spoon", as figure 9 & 16) driving the RFL 2-12.5 alternator at 3000 rpm.

Appendix: Alternator manufacturers.

- MOOG https://www.moog.com/products/alternators.html
- RFL https://rflalternators.com/
- Soga https://www.sogaenergyteam.com/alternators/
- Mecc Alte https://www.meccalte.com/en/products
- NSM http://www.nsmsrl.it/eng/prodotti.php

(a) **MOOG**

6-pole permanent magnet alternators. These do not have a cooling fan (they are mostly used for wind turbines) and the maximum output is very dependent on the airflow; I would need a small electric fan. The "rated power" is for 8-10 m/s air speed but this can be exceeded by 50% given enough cooling (unclear whether this is sensible in terms of life; the voltage would drop further as well). The very high efficiency should mean they need less cooling than ordinary alternators.

Table 1. MOOG GES alternator rated powers.

GES 009		Rated speed (rpm)									
		1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
V2	kw		0,5	0,65	0,8	0,95	1,1	1,2	1,3	1,4	1,5
	eff %		79,9	83,7	86,3	88,1	89,4	90,4	91,2	91,8	92,2
V4	kw	0,7	1	1,3	1,5	1,8	2	2,1	2,3	2,4	2,5
	eff %	82,7	86,8	89,2	90,8	91,9	92,7	93,2	93,6	93,9	94,1
V6	kw	1,1	1,5	1,8	2,1	2,4	2,6	2,8	3		
	eff %	85,4	88,8	90,8	92,1	92,9	93,5	93,9	94,2		
V8	kw	1,5	2	2,4	2,8	3,2	3,4	3,6			
	eff %	87,5	90,4	92	93,1	93,8	94,3	94,5			

GES 013		Rated speed (rpm)									
		600	1000	1500	2000	2500	3000	3500	4000	4500	5000
V2	kw		0,9	1,5	2	2,6	3,1	3,5	3,9	4,2	4,5
	eff %		75,3	83,8	87,6	89,9	91,4	92,4	93,2	93,7	94
V4	kw		1,8	2,8	3,7	4,5	5,2	5,7	6,1		
	eff %		84,9	89,7	92,1	93,4	94,2	94,8	95		
V6	kw	1,1	2,6	3,9	5,1	6,1	6,9	7,2			
	eff %	75,9	88,1	91,8	93,6	94,6	95,1	95,4			
V8	kw	1,8	3,2	4,7	6,1	7,1	7,8				
	eff %	82,4	89,2	92,6	94,1	94,9	95,3				

GES 018		Rated speed (rpm)									
		300	500	750	1000	1250	1500	1750	2000	2250	2500
V2	kw		1,9	3,1	4,2	5,2	6,2	7	7,7	8,3	8,7
	eff %		78,4	85,8	89,1	91	92,3	93,2	93,8	94,2	94,4
V3	kw		2,8	4,3	5,8	7	8,1	9	9,6	10	
	eff %		83,1	88,4	91	92,5	93,5	94,1	94,4	94,6	
V4	kw		3,7	5,6	7,3	8,8	10	10,8	11,1		
	eff %		85,5	90	92,2	93,4	94,1	94,6	94,7		
V6	kw	2,9	5,2	7,7	9,9	11,6	12,7	12,9			
	eff %	80	87,6	91,4	93,1	94,1	94,6	94,6			
V8	kw	3,9	6,7	9,8	12,3	14,1	14,8				
	eff %	82,3	88,9	92,2	93,7	94,4	94,7				

I imagine that bearing replacement requires a MOOG service centre.

Table 2a. It would be convenient if the large and small alternators both generated 240 V rms (star); these 6-pole alternators will however typically produce 100-200 Hz rather than 50 Hz. I am waiting for the rpm per volt data from MOOG for some of these.

Model	Rated rpm	Max data rpm	kW at max rpm (normal cooling)	kW at 3340 rpm	V at 3340 rpm	Rpm for 240 V no load	Nominal power at 240 V speed (kW)	V at nominal load for 240 V
GES009 v2	3000	6000	1.5	0.83	207	3877	1.06	228.5
GES009 v4	3000	6000	2.5	1.4				
GES009 v6	3000	5000	3	2	375	2138	1.6	230
GES009 v8	3000	4500	3.6	2.67				
GES013 v2	3000	5000	4.5	3	369	2170	2.2	226.2
GES013 v4	3000	4000	6.1	5.1	294	2713	4.8	232.3
GES013 v6	3000	3500	7.2	6.9	388	2067	5.2	232.7
GES013 v8	3000	3000	7.8	8.7				
GES018 v2		2500	8.7					
GES018 v3		2250	10					
GES018 v4		2000	11.1					

250 mm PCD gives 1990 rpm so 1.5 kW, 240 V equiv to 2.26 kW, 362v at 3000 rpm

(b) **RFL**
RFL's two-pole permanent magnet alternators offer the possibility of generating close to 50 Hz, 240 V AC which would allow heavy loads (radiators, immersion heater) to be driven directly (Fig. 13) rather than via a large inverter – probably a more reliable solution for the wet weather system. These alternators are single-bearing and would be easy to mount on the end of a two-bearing turbine shaft.

Unfortunately the smallest RFL alternator (RF2-3, 3kVA frame size) is only available as a single-phase variant and the efficiency is not as good as their 3-phase machines.

Table 3. Output parameters for the single-phase version of the RFL2-3 (some old stock still available in Australia; equivalent 3-phase (3 kVA) version not in production except for large orders).

FREQUENCY	50HZ
APPARENT POWER	1.6kVA
RATED POWER	1.3kW
VOLTAGE	230
EFFICIENCY @ 50% LOAD	75.5%
EFFICIENCY @ 75% LOAD	79.89%
EFFICIENCY @ 100% LOAD	79.69%

The 3-phase models are more attractive - the RF2-12.5 (12.5 kVA, 10 kW) in particular would suit the wet weather system.

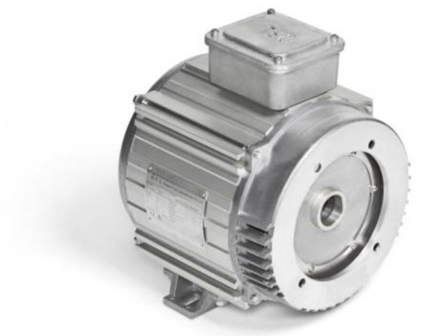


Table 4. 3-phase 2-pole alternator characteristics.

400/420 V - 50Hz - 3000RPM											
MODEL	OPERATING TEMP: 40°C (Cont.) (ΔT = 40°C)								Full (100% Load)		Voltage Transient
	THREE-PHASE		MOTOR START	SHORT CIR.	EFFICIENCY			THD	Current	Torque	
	kVA	kW	kVA	A	1/2	3/4	Full	%	A	N.m	+%, -%
RF2-7.5	7.5	6	7.5	25	90.2	91.5	91.3	1.5	8.5	22.32	0.0/6.0
RF2-12.5	12.5	10	14	46.5	92.7	93.7	93.5	1.5	15.5	33.78	0.0/6.0
RF2-17.5	17.5	14	19	60	95.5	94.3	95.2	1.5	20	46.59	0.0/6.0

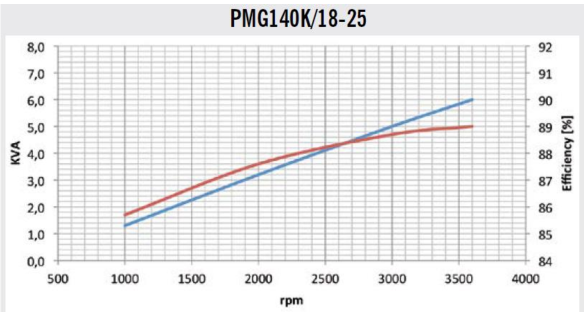
(c) Soga make multi-pole PM alternators but their data sheet does not show efficiency at part load or even the output voltage.

	modules	r.p.m.							
		1000	1500	2000	2500	3000	3500	4000	4500
PMG 90S	1	0,5	0,8	1,1	1,4	1,75	2	2,3	2,7
PMG 90S	2	1,1	1,7	2,4	3,1	3,8	4,4	5,1	5,8
PMG 90L	3	1,7	2,6	3,7	4,7	5,8	6,7	7,8	8,8

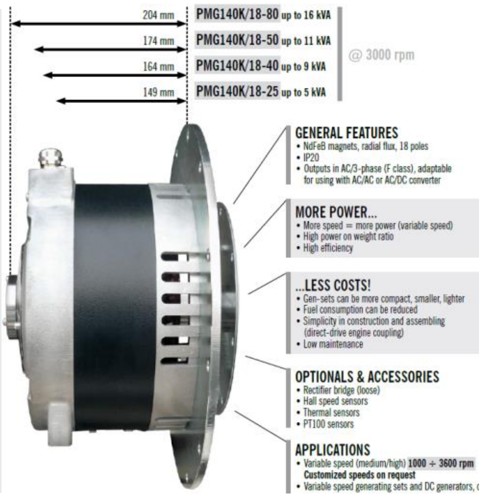
(i) Soga PMG 90, 8-pole output (kW).

	modules	r.p.m.						
		1000	1500	2000	2500	3000	3500	4000
PMG 112	1	1	1,8	2,5	3,1	3,7	4,5	5,2
PMG 112	2	2	3,6	5	6,2	7,4	9	10,5
PMG 112	3	3	5,4	7,5	9,3	11	13,5	15,5
PMG 112	4	4	7,2	10	12,5	14,8	18	21

(ii) Soga PMG 112, 12 pole.



RPM	power AC	efficiency
	KVA	%
1000	1,3	85,7
2000	3,2	87,6
3000	5	88,7
3600	6	89



(iii) Soga PMG140, 18 pole

(d) MeccAlte make brushless alternators from 5 kVA upwards https://www.meccalte.com/

Table 5. Mecc Alte AVR brushless 2-pole alternators

Type 50 Hz	kVA - cosφ 0.8 - 3 Phase continuous CL. H (Δ T= 125°C)				CL. F (ΔT= 105°C)			EFFICIENCY η % CL. H (ΔT= 125°C)			1 Phase kVA
Series Star Y Parallel Star YY Series Delta Δ Parallel Delta ΔΔ	380 190 220 110	400 200 230 115	415 208 240 120	IP45 400 V	380 190 220 110	400 200 230 115	415 208 240 120	2/4	3/4	4/4	COSφ = 1 CL. H (ΔT = 125°C) DELTA
ECP3-1S/2	8	**8**	8	6	7,2	**7,2**	7,2	76	79,5	78,5	5,5
ECP3-2S/2	10	**10**	10	7,5	9	**9**	9	77,5	81	80,5	7
ECP3-3S/2	12,5	**12,5**	12,5	9,5	11	**11**	11	80	83,5	83	8
ECP3-1L/2	16	**16**	16	12	14,5	**14,5**	14,5	81,5	85	84,5	10,5
ECP3-2L/2	20	**20**	20	15,5	18	**18**	18	82,5	86	85,5	12,5

MeccAlte also make alternators for portable generators; efficiency is similar to the equivalent ECP range. https://www.meccalte.com/en/products/portable

Table 6. Mecc Alte brushless 2-pole single phase "portable" alternators:

Type	115/230V 50Hz 3000 RPM kVA CL. H	η 2/4 1 p.f. %	η 3/4 1 p.f. %	η 4/4 1 p.f. %	T.H.D. %	Air volume m³/min	Noise 7m dBA	Noise 1m dBA	Weight Kg	J Kgm²
S15W-45	1,2	65,9	68,8	68,7	< 5	2,1	55	71	8,1	0,0031
S15W-60	1,8	67,5	70,4	70,2	< 5	2,1	55	71	10,4	0,0040
S15W-75	2,1	68,8	71,6	71,4	< 5	2,1	55	71	12,4	0,0049
S15W-85	2,4	69	71,9	71,8	< 7,5	2,1	55	71	13,4	0,0055
S15W-102	2,8	89,2	72,2	72	< 5	2,1	55	71	14,8	0,0066

Table 7. Mecc Alte 2-pole brush + AVR "portable" alternators.

Type	POWER 230/400 V at 3000 RPM - 50 Hz CL. H (ΔT=125°C) THREE-PHASE KVA	KW cos φ 0,8	MOTOR STARTING CAPABILITY KVA	EFFICIENCY 2/4 %	3/4 %	4/4 %	CL. F (ΔT=105°C) THREE-PHASE KVA	KW cos φ 0,8	CL. H (ΔT=125°C) SINGLE-PHASE KVA cos φ 1	MOTOR STARTING CAPABILITY KVA	T.H.D. %
T20FS-130	**10**	8	40	78	82,1	81,5	9	7,2	6,5	KVA 25	< 5
T20FS-160	**12,5**	10	45	78,5	82,5	82	11,5	9,2	8,5	KVA 32	< 5
T20F-200	**15**	12	54	79,1	83,1	82,6	14	11,2	10	KVA 38	< 5

(e) **NSM** http://www.nsmsrl.it/eng/prodotti.php , brochure http://www.nsmsrl.it/UserFiles/file/catgen.pdf?d=1557233759?time=now() make a wide range of alternators for portable generators.

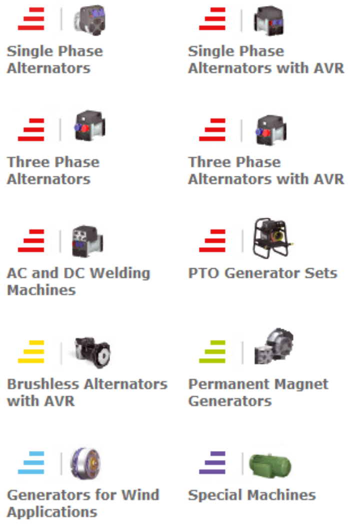


Table 8. NSM 2-pole alternator examples

Model	kVA	η (%)	Phases	Brush/brushless	Cap/AVR
K80A	1.5	70.5	1	BL	Cap
K80D	3	73	1	BL	Cap
C112SB	10	79.5	1	BL	Cap
KR80B	2.2	73.5	1	B	AVR
CR112SB	10	80.5	1	B	AVR
ZR100LB	10	85	3	B	AVR

Table 9. NSM Permanent magnet generators

Modello Model	Potenza Output Power	Rendimento Efficiency	Range di utilizzo Range of use	Peso Weight				
	1 ph [kVA]	(PMG + inverter) η%	[rpm]	PMG cone	PMG SAE 5 *	Inverter	EMC filter	rpm reg. kit
				[kg]				
PMG-I 1ph 150 SB	**3**	0,87	2000 ÷ **3000** 2400 ÷ **3600**	9	---	5,5	1,3	2
PMG-I 1ph 150 SC	**6**	0,87	2000 ÷ **3000** 2400 ÷ **3600**	10	---	10	2	2
PMG-I 1ph 185 SC	**10**	0,87	2000 ÷ **3000** 2400 ÷ **3600**	14,5	14	10	3	2
PMG-I 1ph 185 SF	**10**	0,88	1700 ÷ **2400** 1900 ÷ **2700**	17,5	17	10	3	2