Electronic Supplementary Information for "Mapping the Frontiers of Quinone Stability in Aqueous Media: Implications for Organic Aqueous Redox Flow Batteries"

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Contents

S1 Calibration of Reduction Potentials with PM7 and B3LYP Methods

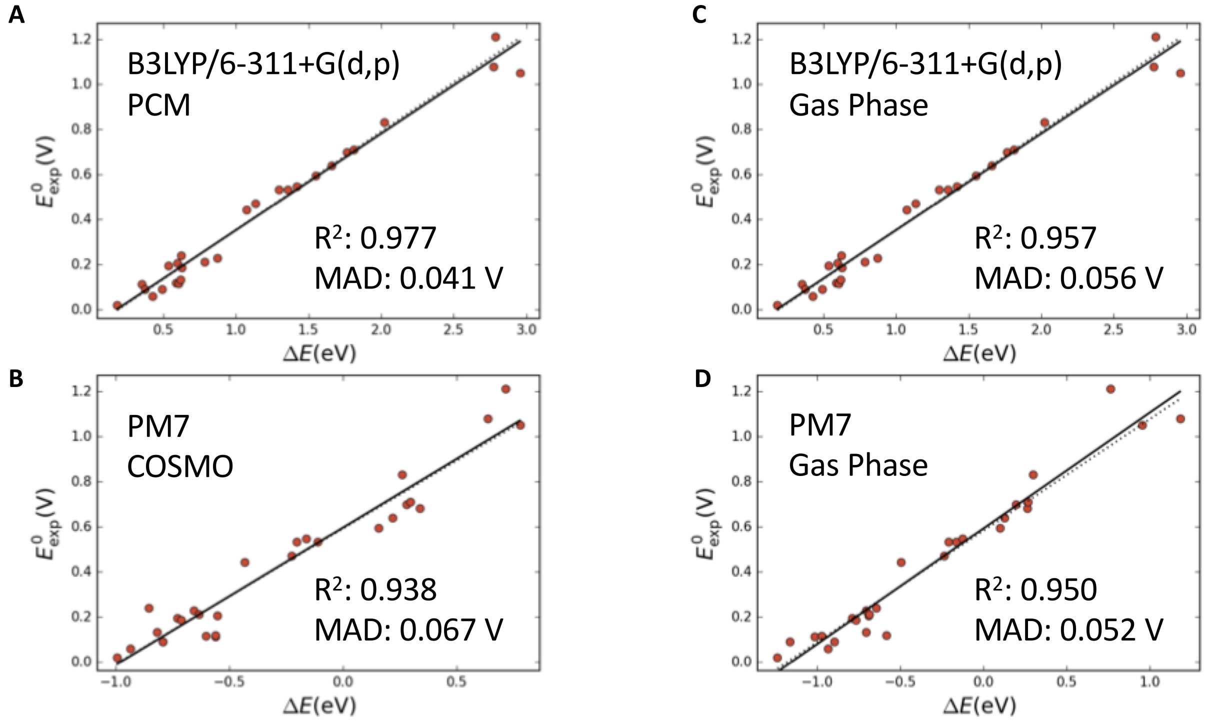


Figure S1: Calibration of the computed reduction potentials of quinones with PM7 COSMO and B3LYP/6-311+G(d,p) PCM methods. ΔE refers to the calculated reaction energy of oxidized form and H_2 combining to form the reduced hydroquinone at the given level of theory and E^0_{exp} refers to the measured reduction potential at pH = 0 vs. SHE. The values of the previously measured standard reduction potentials and the identities of the molecules are tabulated in Table S1.

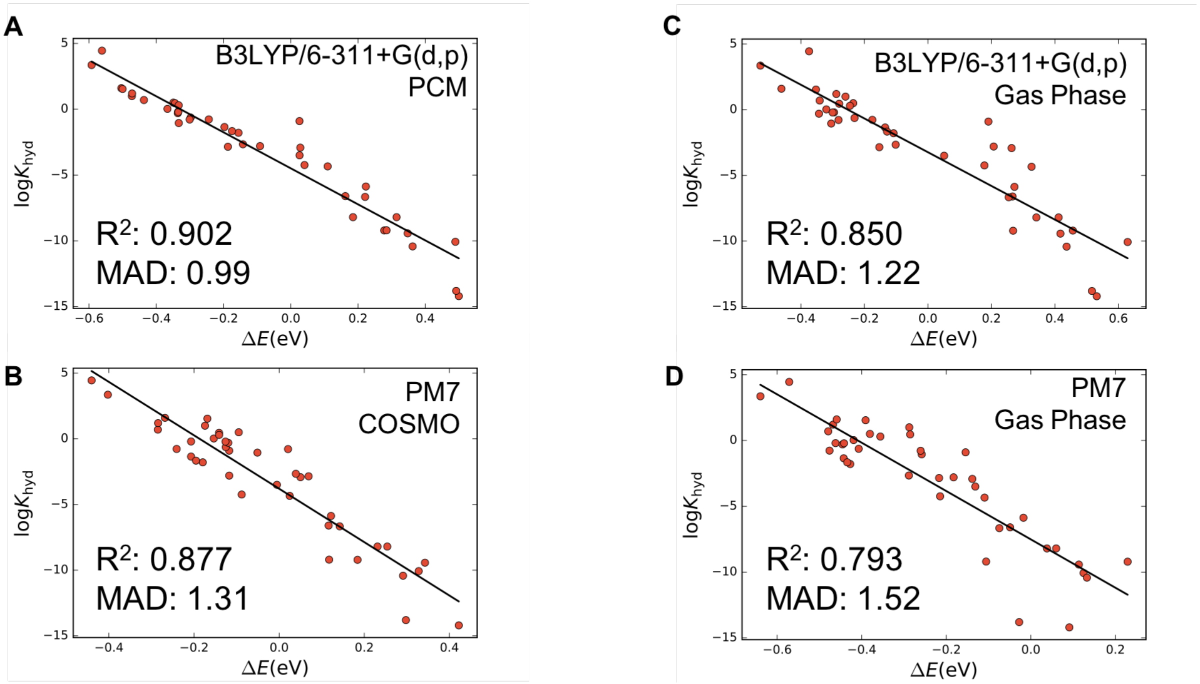


Figure S2: Calibration of the gem diol equilbrium constant, $\log K_{\mathrm{hyd}}$, with PM7 COSMO and B3LYP/6-311+G(d,p) PCM methods. ΔE refers to the calculated reaction energy of a ketone and water combining to form a gem diol at the given level of theory. and E^0_{exp} The values of the previously measured standard reduction potentials and the identities of the molecules are tabulated in Table S2. These results were first reported in Ref. S1

S2 Experimental Calibration Points for Theoretical Methods

Note: In the case of multiple ketone groups (as is the case with all quinones), the reported $\log K_{\mathrm{hyd}}$ is for the most thermodynamically favorable reaction for the formation of a gem diol.

Table S1: Reference Data for Calibration of Reduction Potentials

Molecule SMILES	E^0_{exp} vs. SHE (V) at pH = 0
Oc1c(Cl)c(Cl)c(O)c(Cl)c1Cl	0.683
O=S(=O)(O)Cc1c(CS(=O)(=O)O)c(O)c2c(O)c3ccccc3c(O)c2c1O	0.02
O=S(=O)(O)CCSc1c(SCCS(=O)(=O)O)c(O)c2c(O)c3ccccc3c(O)c2c1O	0.113
O=S(=O)(O)c1cc(O)c2c(O)c3ccccc3c(O)c2c1O	0.09
O=S(=O)(O)c1cc2c(O)c3ccccc3c(O)c2c(O)c1O	0.06
Oc1c2ccccc2c(O)c2ccccc12	0.09
O=S(=O)(O)c1cccc2c(O)c3ccccc3c(O)c12	0.195
O=S(=O)(O)c1ccc2c(O)c3ccc(S(=O)(=O)O)c(O)c3c(O)c2c1O	0.118
O=S(=O)(O)c1cccc2c(O)c3cccc(S(=O)(=O)O)c3c(O)c12	0.206
O=S(=O)(O)c1ccc2c(O)c3c(O)c(S(=O)(=O)O)ccc3c(O)c2c1O	0.116
O=S(=O)(O)c1ccc2c(O)c3c(O)c(O)c(S(=O)(=O)O)cc3c(O)c2c1	0.133
O=S(=O)(O)c1cccc2c(O)c3c(S(=O)(=O)O)cccc3c(O)c12	0.239
O=S(=O)(O)c1ccc2c(O)c3ccccc3c(O)c2c1	0.187
O=S(=O)(O)c1ccc2c(O)c3ccc(S(=O)(=O)O)cc3c(O)c2c1	0.213
O=S(=O)(O)c1ccc2c(O)c3cc(S(=O)(=O)O)ccc3c(O)c2c1	0.228
Oc1c(O)c2ccccc2c2ccccc12	0.442
Oc1ccc(O)c2ccccc12	0.47
O=S(=O)(O)c1cccc2c(O)ccc(O)c12	0.532
O=S(=O)(O)c1ccc2c(O)ccc(O)c2c1	0.534
Oc1ccc2ccccc2c1O	0.547
Oc1ccc(O)c(O)c1	0.594
Cc1cc(O)ccc1O	0.641
Oc1ccc(O)cc1	0.699
Oc1ccc(O)c(Cl)c1	0.71
Oc1ccccc1O	0.831
O=C1c2ccccc2C(=O)c2c(O)c(SCCS(=O)(=O)O)c(SCCS(=O)(=O)O)c(O)c21	1.08
O=C1c2ccccc2C(=O)c2c1cc(S(=O)(=O)O)c(O)c2O	1.21
O=C1c2ccccc2C(=O)c2c(O)c(S(=O)(=O)O)cc(O)c21	1.05

Experimental reduction potentials obtained from Ref. S2.

Table S2: Reference Data for Calibration of $\log K_{\mathrm{hyd}}$

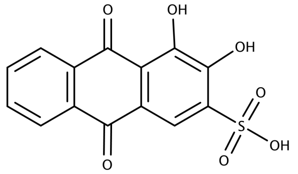
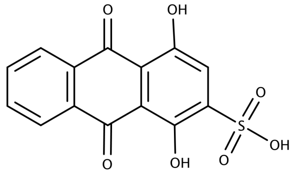
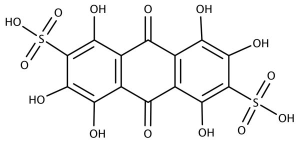
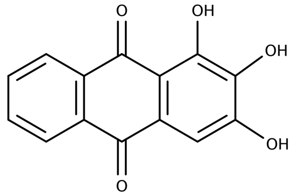
Molecule SMILES	$\log K_{\mathrm{hyd}}$	Molecule SMILES	$\log K_{\mathrm{hyd}}$
COC(=O)C(F)F	-2.92	CC(C)=O	-2.85
CCC(=O)OC	-9.43	CCCC=O	-0.3
O=C1CCC1	-2.66	O=CCCl	1.6
O=C(CCl)CCl	1.0	O=Cc1ccc(Cl)c(Cl)c1	-1.35
C=O	3.36	COC(=O)c1ccccc1	-10.07
COC(=O)C(Cl)(Cl)Cl	-4.24	CC(=O)CF	-0.78
COC(=O)C(F)(F)F	-0.9	CCSC(C)=O	-8.2
CCSC(=O)C(F)(F)F	-2.8	COC(=O)C(Cl)Cl	-4.34
COC=O	-6.6	COC(=O)CC#N	-5.87
CC=O	0.03	O=Cc1ccc(Cl)cc1	-1.79
CC(=O)N(C)C	-14.2	COC(=O)CCl	-6.66
COCC(=O)OC	-9.21	O=Cc1ccc([N+](=O)[O-])cc1	-0.77
COC(C)=O	-8.2	CC(=O)C(F)(F)F	1.54
CC(=O)CCl	-1.05	COC(=O)C(C)=O	0.5
CC(C)(Cl)C=O	0.7	O=Cc1cccc(Cl)c1	-1.66
CCC=O	-0.2	O=Cc1ccccc1	-2.1
CCC(Br)C=O	0.6	CN(C)C(=O)C(F)(F)F	-9.2
CCC(Br)(Br)C=O	1	CC(=O)C(Cl)Cl	0.46
CCC(Cl)C=O	1.2	CC(C)C=O	-0.21
CC(C)(C)C=O	-0.63	CCSC=O	-3.5
CN(C)C=O	-13.8	COC(=O)C(C)C	-10.42
O=CC(Cl)(Cl)Cl	4.45	CC(=O)C(C)=O	0.3

Experimental hydration equilibrium constants obtained from Ref. S3.

S3 Summary of Experimental Stability Results

Cyclic voltammetery results were obtained under the following conditions: 5-10 mM concentration of the molecule in 1M H_2SO_4. Scanning rate is 100 mV/s. The working electrode is a glassy carbon electrode. The counter electrode is a platinum wire and the reference electrode is Ag/AgCl. Potentials are vs. SHE and the third CV cycle is plotted.

Table S3: Theoretical Predictions of Experimentally-Tested Fused Quinones

Molecule Name	Structure (Reduced Form)	$\log K_{\mathrm{hyd}}^{a}$	$\Delta E_{mic}(eV)^{a}$
Alizarin red S		0.63	0.03
Quinizarin 2-sulfonic acid		0.43	0.37
Alizarin blue 2B		5.53	0.42
Anthracene brown		2.82	*b*

[a] Calculated with PM7 COSMO for oxidized form

[b] No Michael addition/substitution site according to formulated rules.

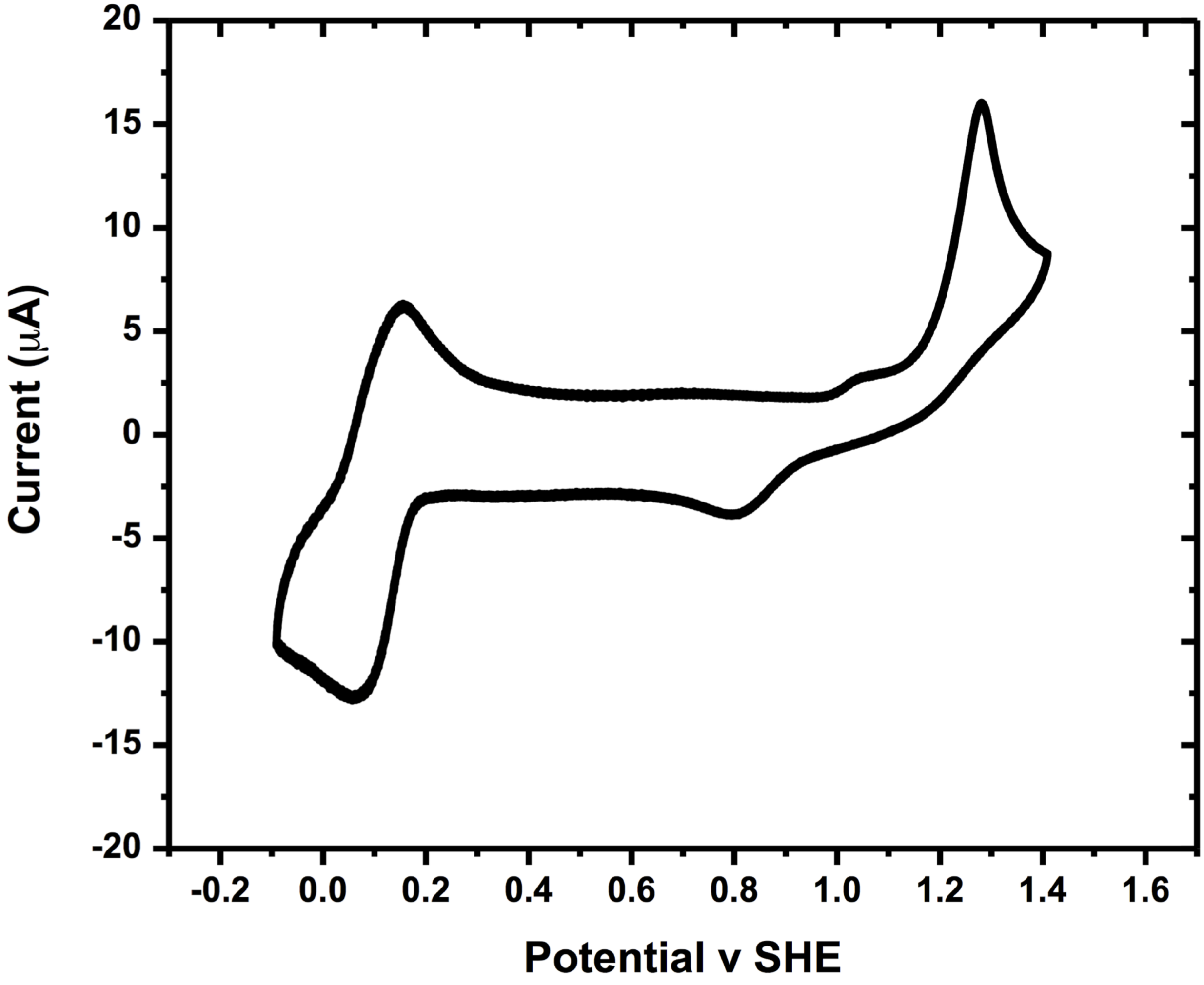


Figure S3: CV of quinizarin 2-sulfonic acid

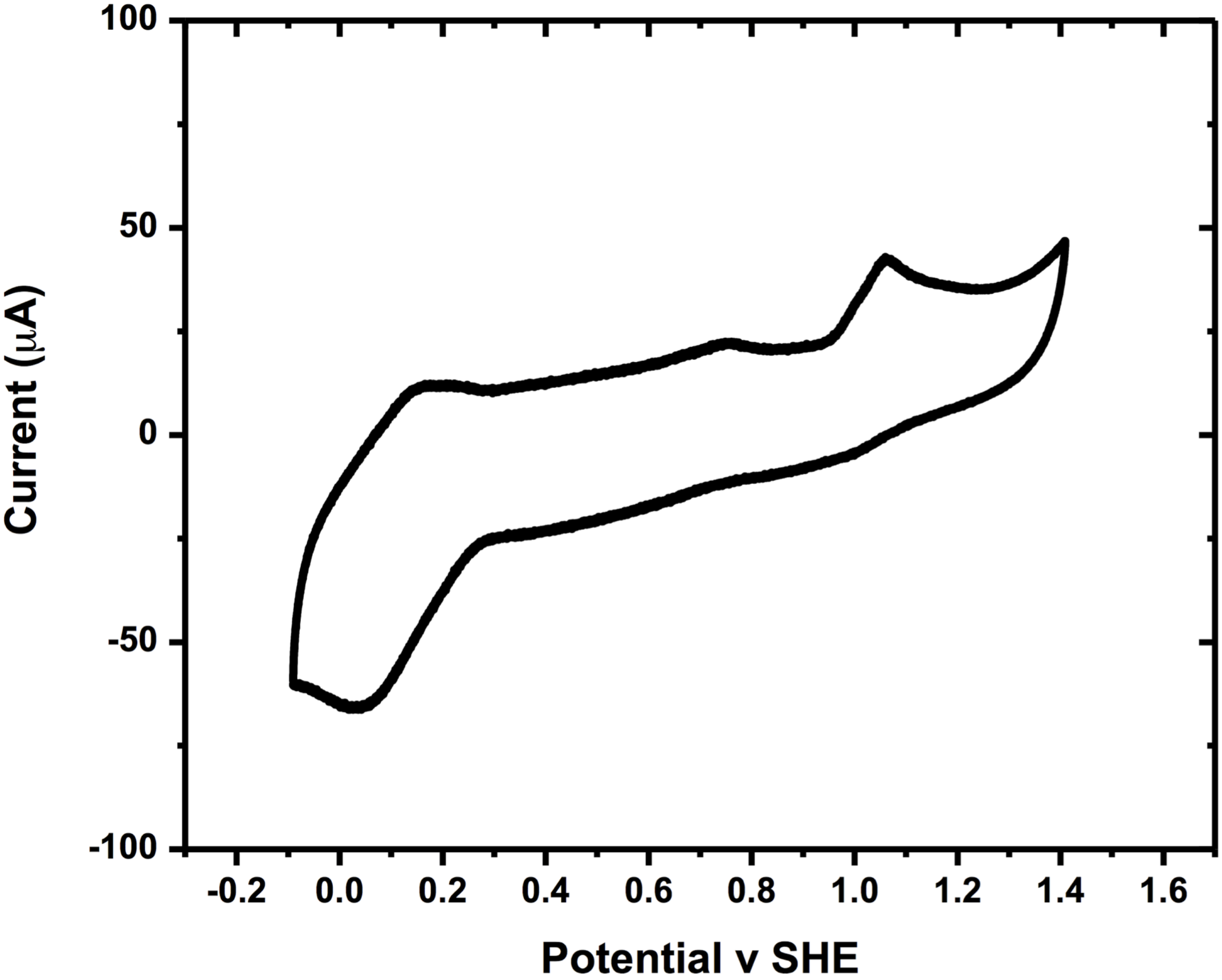


Figure S4: CV of alizarin blue 2B

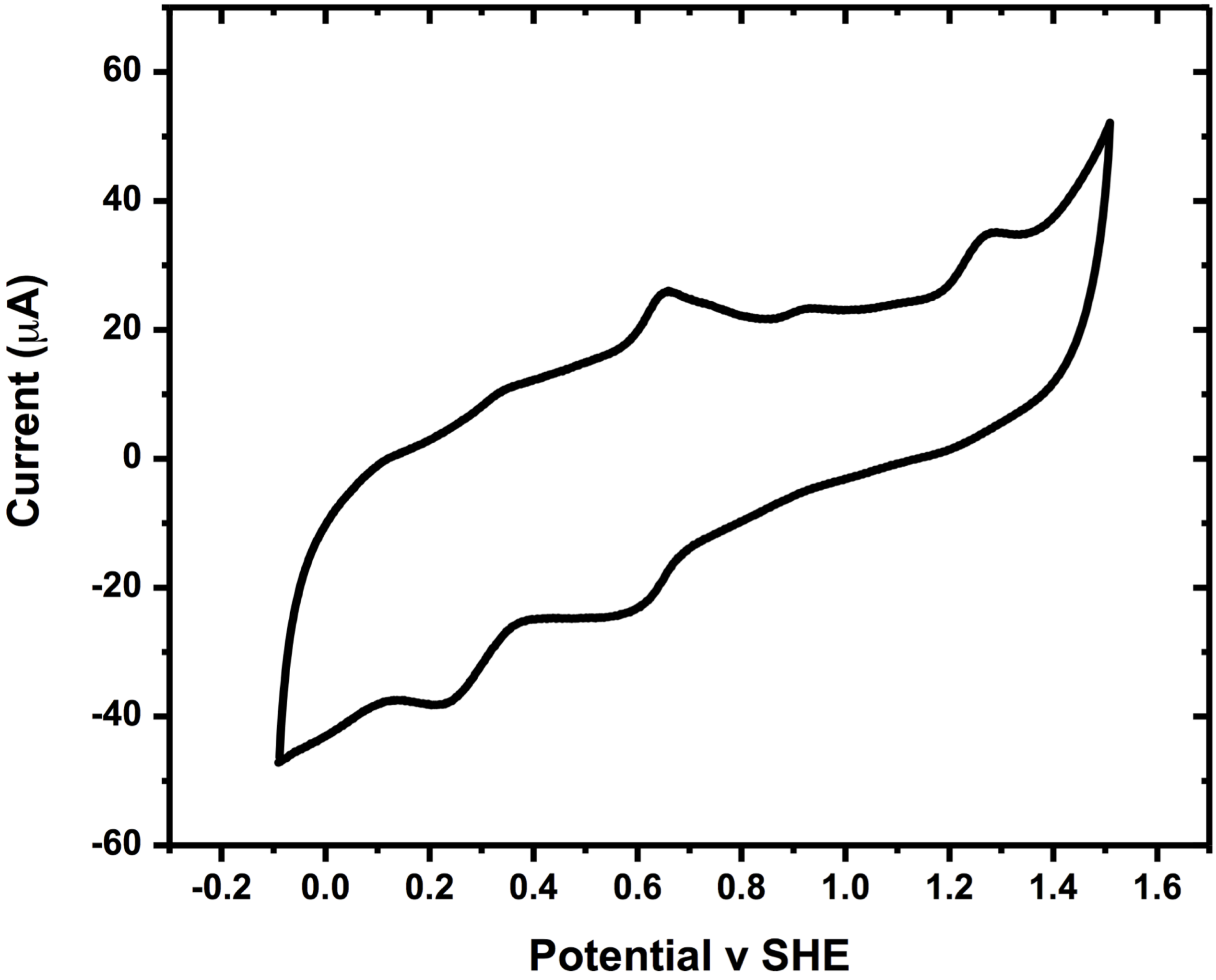


Figure S5: CV of anthracene brown

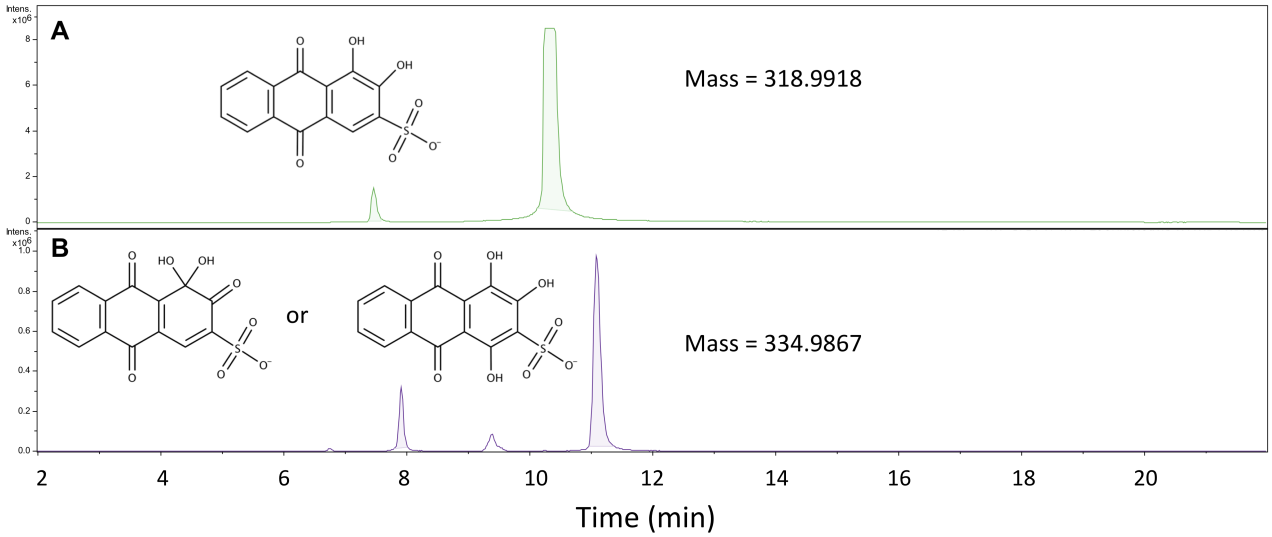


Figure S6: A) LC-MS Spectrum corresponding to starting material, alizarin red S. The two peaks are assigned to different substitution sites of the sulfonate group obtained from the manufacturer, with the dominant material being the depicted structure and the impurity having a sulfonate functionalization at the 7 or 8 position. B) LC-MS spectrum corresponding to the starting material with an additional H_2O mass (after charging). Based on the relative ratios of the starting material to impurities, the peaks at 8 min and 11 min most likely correspond to the Michael addition and gem-diol products of alizarin red S and the much smaller peaks correspond to analogous product(s) in the impurity.

S4 Chemical Synthesis of Oxidized Quinizarin

The oxidized form of quinizarin was chemically synthesized according to literature preparation (Figure S7A).[S4] The fact that the oxidized quinizarin can be synthesized meant that the molecule itself was accessible. However, by stirring in 1 M sulfuric acid, a solvent often used for flow battery applications, 20 % of the quinizarin was attacked by water and turned into purpurin (Figure S7B). It is worth noting that the solubility of oxidized quinizarin in sulfuric acid was very limited, and in the above model water addition was a heterogeneous reaction. It is conceivable that in a real flow battery setting when a sulfonated fused quinone is employed, the rate of water attack will be orders of magnitude faster.

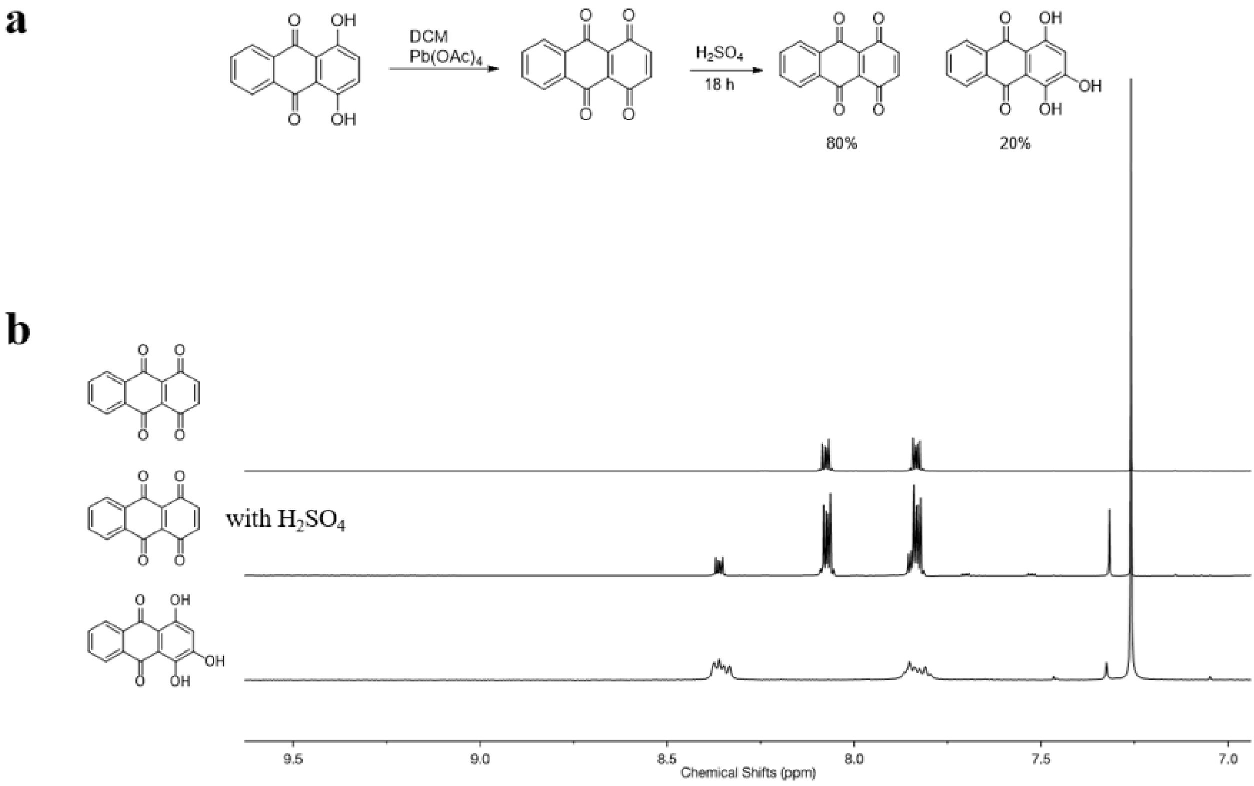
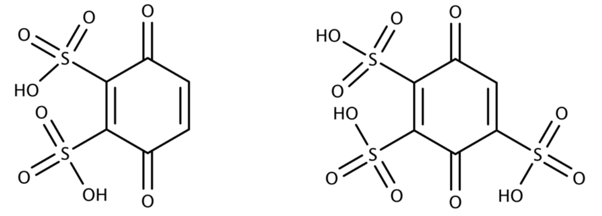


Figure S7: a) Synthesis of oxidized quinizarin. b) NMR spectra of synthetic oxidized quinizarin(top), quinizarin stirred with sulfuric acid (middle), purpurin standard (bottom). NMR spectra were recorded on Varian INOVA 500 spectrometers in solutions of deuterated chloroform (CDCl3)

S5 Molecules with Small Changes in Redox Properties Upon Michael Addition



$E^0 = 1.05$ V $\quad$ $E^0 = 1.10$ V

$\Delta E^0_{\text{michael prod}} = -0.03$ V $\quad$ $\Delta E^0_{\text{michael prod}} = -0.17$ V

Figure S8: Two molecules (from Figure 3) that are calculated to have reduction potentials > 1.00 V vs. SHE at pH = 0 and have Michael addition products that have a change in reduction potential from the parent molecule of less than 0.20 V. Note that the products of Michael addition of these molecules are also subject to a second Michael addition and the reduction potential further decreases. The reduction potential of the dihydroxy, disulfonic acid substituted quinones is calculated be $\sim$0.80 V vs. SHE.

S6 Molecules that Pass Screening Criteria

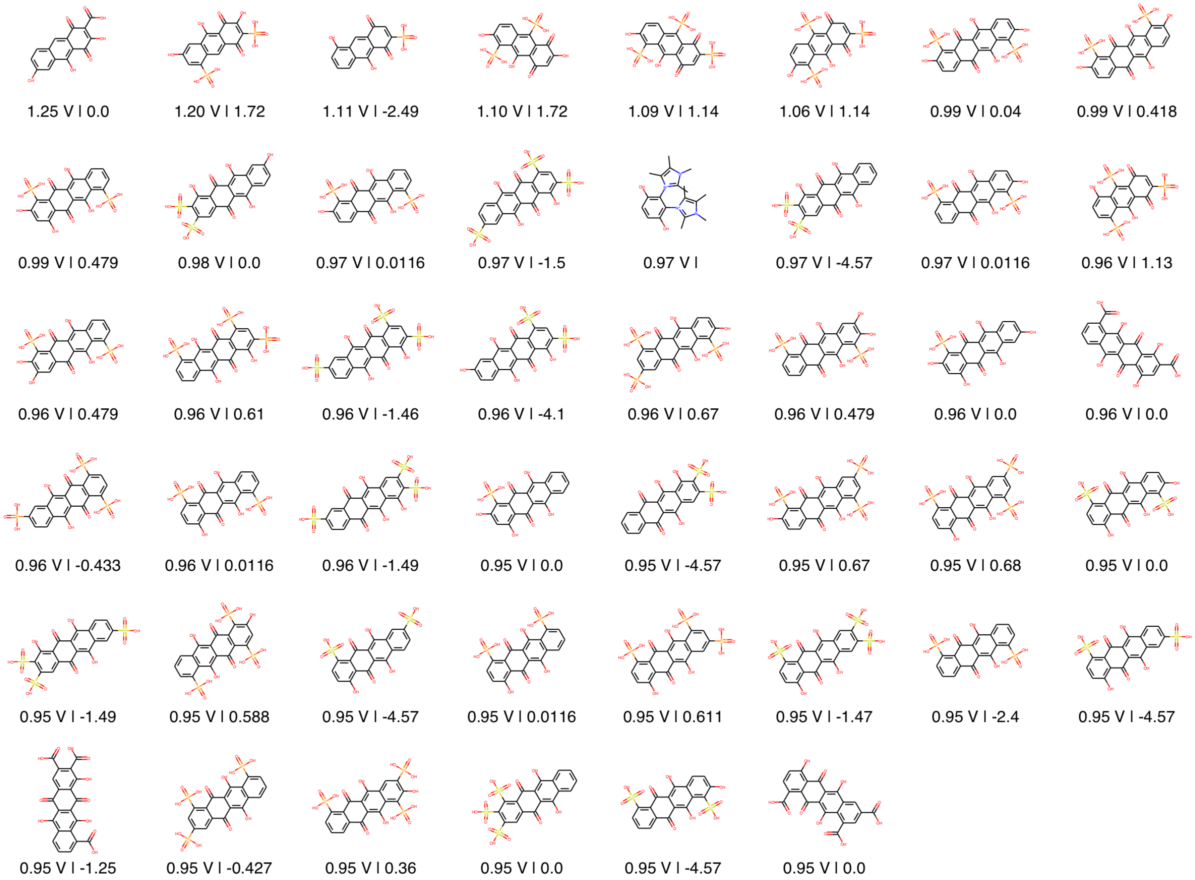
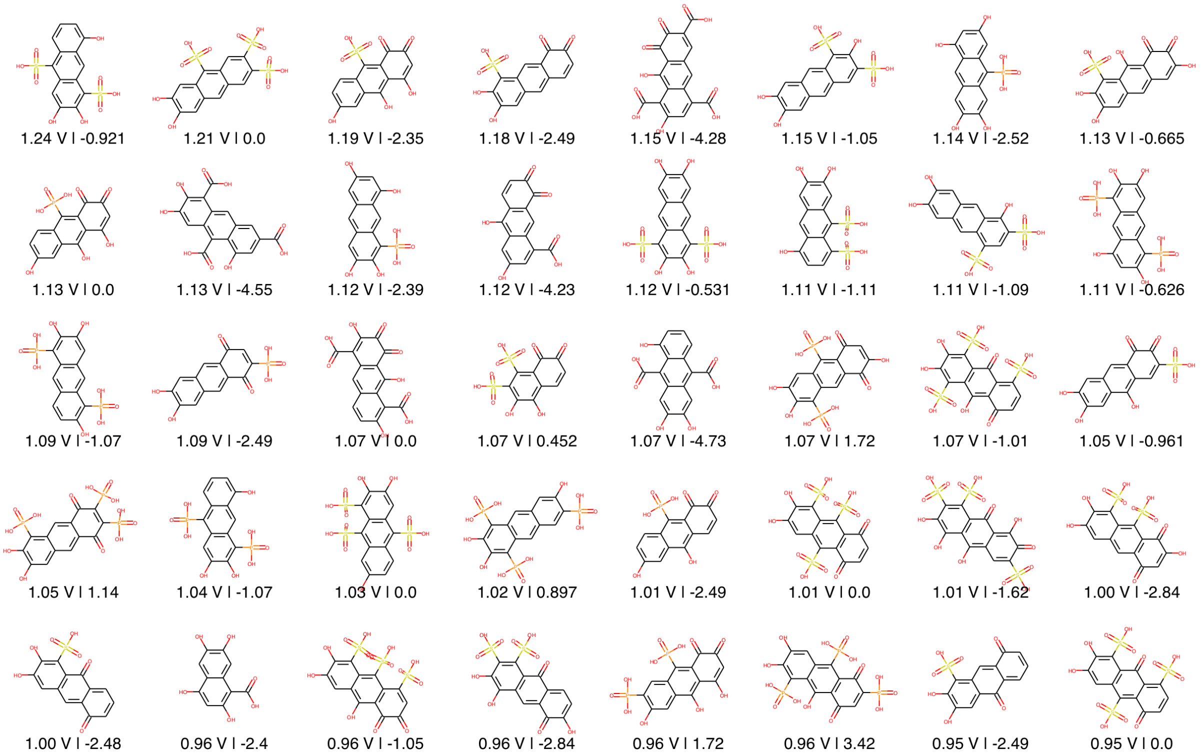


Figure S9: The reduced form of the 46 couples from the virtual screening that lack phenanthrene backbones and catechol redox topologies and have oxidized forms satisfying the following criteria: $\log K_{\mathrm{hyd}} < 1.0$, $\Delta E_{mic} < 0.03$ eV, and reduction potentials > 0.95 V vs. SHE according to the calibrated PM7 COSMO level of theory results. The predicted potentials, based on the calibrated PM7 COSMO computations, are shown underneath each molecule (on the left). The right value under each molecule is the estimated Log (base 10) of the solubility of the (oxidized, and solubility-limiting form) molecule, calculated with ChemAxon. The calculation is only valid for molecules with no net-charge (with the exception of deprotonation). The attached screened_molecules.xlsx spreadsheet also includes calculated solubilities at pH = 7 and PM7 COSMO solvation free energies.



1.24 V | -0.921
1.21 V | 0.0
1.19 V | -2.35
1.18 V | -2.49
1.15 V | -4.28
1.15 V | -1.05
1.14 V | -2.52
1.13 V | -0.665
1.13 V | 0.0
1.13 V | -4.55
1.12 V | -2.39
1.12 V | -4.23
1.12 V | -0.531
1.11 V | -1.11
1.11 V | -1.09
1.11 V | -0.626
1.09 V | -1.07
1.09 V | -2.49
1.07 V | 0.0
1.07 V | 0.452
1.07 V | -4.73
1.07 V | 1.72
1.07 V | -1.01
1.05 V | -0.961
1.05 V | 1.14
1.04 V | -1.07
1.03 V | 0.0
1.02 V | 0.897
1.01 V | -2.49
1.01 V | 0.0
1.01 V | -1.62
1.00 V | -2.84
1.00 V | -2.48
0.96 V | -2.4
0.96 V | -1.05
0.96 V | -2.84
0.96 V | 1.72
0.96 V | 3.42
0.95 V | -2.49
0.95 V | 0.0

Figure S10: Sampling of the reduced forms of the 377 couples from the virtual screening that lack phenanthrene backbones and but have catechol and have oxidized forms satisfying the following criteria: $\log K_{\text{hyd}} < 1.0$, $\Delta E_{mic} < 0.03$ eV, and reduction potentials > 0.95 V vs. SHE according to the calibrated PM7 COSMO level of theory results. The predicted potentials, based on the calibrated PM7 COSMO computations, are shown underneath each molecule. Solubilities computed in the same way as above are also indicated and included in the screened_molecules.xlsx spreadsheet.

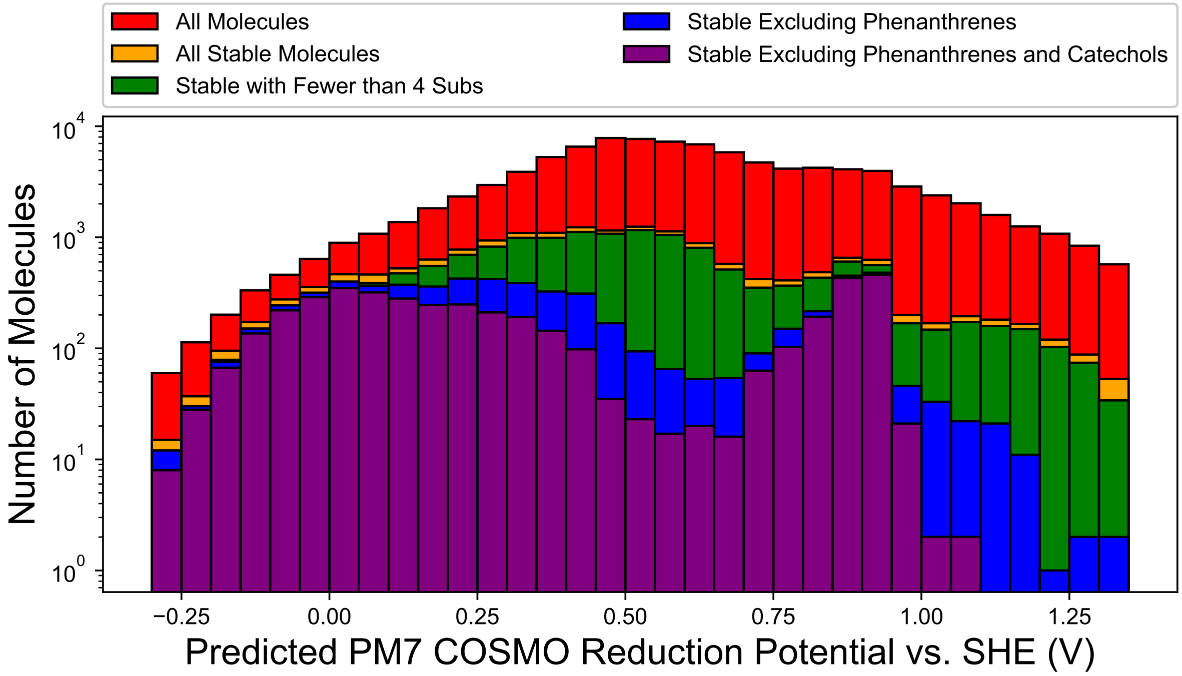


Figure S11: Plot of the reduction potential distributions of various sets of molecules, as indicated in the legend. Molecules are defined as "stable" if they have the following criteria 1) PM7 COSMO Michael addition energy < 0.00 eV and 2) $\log K_{\mathrm{hyd}} < 0.0$. These are stricter criteria than in the main text.

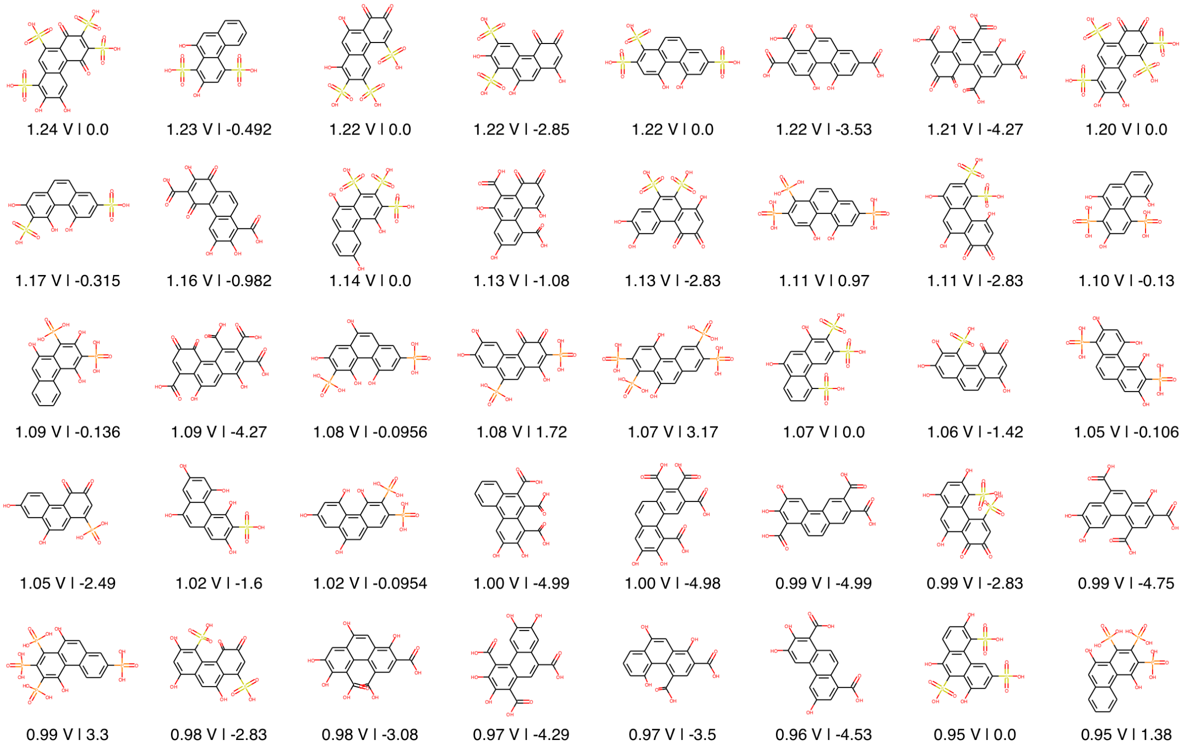
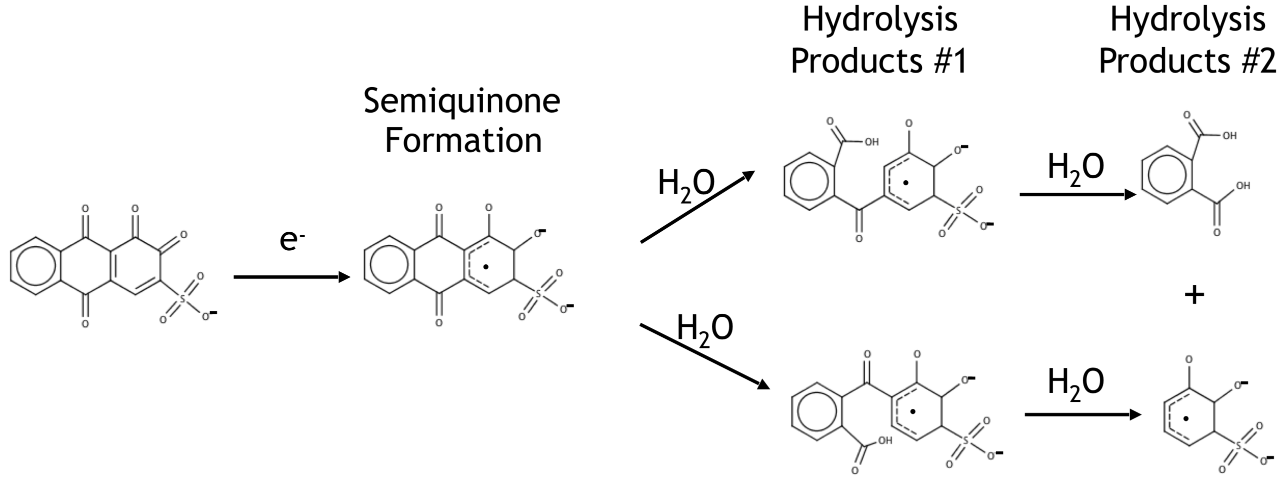

1.24 V | 0.0
1.23 V | -0.492
1.22 V | 0.0
1.22 V | -2.85
1.22 V | 0.0
1.22 V | -3.53
1.21 V | -4.27
1.20 V | 0.0
1.17 V | -0.315
1.16 V | -0.982
1.14 V | 0.0
1.13 V | -1.08
1.13 V | -2.83
1.11 V | 0.97
1.11 V | -2.83
1.10 V | -0.13
1.09 V | -0.136
1.09 V | -4.27
1.08 V | -0.0956
1.08 V | 1.72
1.07 V | 3.17
1.07 V | 0.0
1.06 V | -1.42
1.05 V | -0.106
1.05 V | -2.49
1.02 V | -1.6
1.02 V | -0.0954
1.00 V | -4.99
1.00 V | -4.98
0.99 V | -4.99
0.99 V | -2.83
0.99 V | -4.75
0.99 V | 3.3
0.98 V | -2.83
0.98 V | -3.08
0.97 V | -4.29
0.97 V | -3.5
0.96 V | -4.53
0.95 V | 0.0
0.95 V | 1.38

Figure S12: Sampling of the reduced forms of the 1545 couples with phenanthrene backbones that are predicted to be stable. These couples have oxidized forms with predicted $\log K_{\mathrm{hyd}} < 1.0$ and are predicted to have reduction potentials > 0.95 V vs. SHE. These do not have a predicted Michael attack site, but are challenging to synthesize. The predicted potentials, based on the calibrated PM7 COSMO computations, are shown underneath each molecule. Solubilities computed in the same way as above are also indicated and included in the screened_molecules.xlsx spreadsheet.

S7 Potential Ring Opening Decomposition Mechanism



Scheme S1: Potential semiquinone-initiated ring-opening decomposition. This scheme is inspired by an analogous mechanism previously proposed by Yamamoto *et al.* for alizarin red S in the presence of hydrogen peroxide.[S5] In this case, the nucleophile is water (as opposed to the hydroxide anion) and the radical source comes from electrochemical cycling (as opposed to hydrogen peroxide).

References

[S1] Lin, K.; Gómez-Bombarelli, R.; Beh, E. S.; Tong, L.; Chen, Q.; Valle, A.; Aspuru-Guzik, A.; Aziz, M. J.; Gordon, R. G. A redox-flow battery with an alloxazine-based organic electrolyte. *Nat. Energy* **2016**, *1*, 16102.

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